‘The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions’.

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MPhil Thesis: September 2013
To my wife,

who takes care of me and makes my

life fruitful and happy.

To my parents,

who took care of me during my childhood and
gave me the chance
to become conscious and creative.

To my brother,

who always keeps an eye to me during my long trips
and remains a best friend.
‘You are allowed to ‘fall down’; you must ‘get up’ quickly’.

Επιτρέπεται να πέσεις, Επιβάλλεται να σηκωθείς.

Pablo Garcia

Thereupon many statesmen and philosophers came to Alexander the Great with their congratulations, and he expected that Diogenes of Sinope would also do likewise. But since that philosopher took not the slightest notice of Alexander, and continued to enjoy his leisure in the suburb Craneion, Alexander went in person to see him; and he found him lying in the sun. Diogenes raised himself up a little when he saw so many people coming towards him, and fixed his eyes upon Alexander. And when Alexander addressed him with greetings, and asked if he wanted anything, “Yes,” said Diogenes, “stand a little out of my sun.” It is said that Alexander was admired so much the haughtiness and grandeur of the man who had nothing but scorn for him, that he said to his followers, who were laughing about the philosopher as they went away, “But truly, if I were not Alexander, I would be Diogenes.”

Plutarch, ‘Parallel Lives’
Author’s prologue.

‘Three years ago, I met the Jet Grouting technique. It intrigued me from the very first moment. Being almost addicted to it, I have understood that executing Jet Grouting is a ‘constant fight’ with the soil erosion ability; the whole team (Foreman, Drilling Operator, High pressure pump Operator, Helpers + support Engineers) directed by the Site Manager, reacts as the Spartan phalanx; the phalanx meets its enemy (soil that has to be treated) with enough momentum and pressure (400 bar) to move forward, but it also maintains order within the ranks so not to allow gaps between columns. The importance of unity and cohesion among Jet Grouting’ troops’ cannot be overemphasized. One weak link in the chain of ‘infantrymen’ could create a gap that can be potentially ‘fatal’ if exploited. Having the role of Site Manager, I choose the best ‘troops’ in the front and rear lines and have created my Jet Grouting phalanx; a phalanx which has never been defeated, which supported me in the execution of this thesis and remains active for my further steps in the fields of research’.

‘The willingness to learn is the greatest virtue that a human being requires in order to gain creativity and successes.’

‘The current thesis has been purely executed by me and all the used information from other sources is referenced.’

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Thomas Kimpritis
Abstract

Jet Grouting is widely used in the global geotechnical market and is a well-known technology: notwithstanding, it does remain a state-of-the-art technique, a useful tool at the disposal of Geotechnical Engineers and Site Managers and there is still scope for improvement both in construction practice and design. This thesis focuses on two crucial themes required for quality control: (i) the diameter of the Jet Grouting elements and (ii) the achieved strength of its body. First, the method is explained and the main issues of the Jet Grouting concept are highlighted. A description follows of the diameter control techniques available in the geotechnical industry along with various issues and definitions regarding the strength. Next, case studies, from which various data were gathered, are reported and the thesis is developed with an extended data analysis using graphs and charts. The influence of the ground conditions and soil type on the achieved diameter and strength are also examined. The current document concludes with the mapping of Jet Grouting ‘parameters’, an evaluation of the available diameter control methods and proposals about the way that the Jet Grouting strength can be assessed. A new concept and approach to measure the diameter of a Jet Grouting element on site is developed based on the main factors that influence its size: the executional parameters, the equipment, the grout utilised and the soil conditions.
Περίληψη

Η τεχνική του Jet Grouting (Ενεματώσεις υψηλών πιέσεων με αποτέλεσμα την υδραυλική διάβρωση της εδαφικής μάζας και κατασκευής εδαφοπασσάλων) είναι γνωστή σε παγκόσμιο επίπεδο και χρησιμοποιείται σε ευρύ φάσμα γεωτεχνικών εφαρμογών. Παραμένει μέχρι και σήμερα μία εξειδικευμένη τεχνική με συνεχή ανάπτυξη και εξέλιξη και για αυτό αποτελεί ένα σημαντικό εργαλείο στα χέρια του Γεωτεχνικού Μηχανικού. Η παρούσα διπλωματική εργασία επικεντρώνεται στις αρχές της τεχνικής του Jet Grouting και αναλύει δύο από τα βασικά θέματα ενός ποιοτικού ελέγχου που εφαρμόζεται σε γεωτεχνικά έργα τα οποία εφαρμόζεται η μέθοδος αυτή, τη διάμετρο των εδαφοπασσάλων και την αντοχή τους. Στην αρχή της παρούσας εργασίας, αναλύεται η μέθοδος καθώς και οι βασικές αρχές της εφαρμογής της. Ακολουθεί η περιγραφή όλων των διαθέσιμων στην αγορά μεθόδων μέτρησης της διαμέτρου και ταυτόχρονα πραγματοποιείται και η κατηγοριοποίηση τους με βάση το τρόπο εκτέλεσης τους. Επίσης, αναφέρονται οι ορισμοί και τα θεμελιώδη στοιχεία για την ανάλυση της αντοχής του σώματος του Jet Grouting. Στη συνέχεια, περιγράφονται με ενδελεχεία οι γεωτεχνικές εφαρμογές της μεθόδου πάνω στις οποίες πραγματοποιήθηκαν εκτεταμένες μετρήσεις και συλλέχθηκαν στοιχεία τα οποία παρουσιάζονται και αναλύονται καθώς και με τη μορφή διαγραμμάτων. Εξετάζεται ακόμη η επιρροή του εδάφους στην επιτυγχανόμενη διάμετρο και στην τελική αντοχή των στοιχείων των εδαφοπασσάλων. Η διπλωματική εργασία ολοκληρώνεται με την ανάλυση όλων των παραγόντων που επηρεάζουν την αποδοτικότητα και το βαθμό επιτυχίας του Jet Grouting, την αξιολόγηση και σύγκριση των μεθόδων μέτρησης της διαμέτρου των εδαφοπασσάλων καθώς και με προτάσεις για την αξιολόγηση της αντοχής των δειγμάτων. Επίσης πραγματοποιείται η ανάπτυξη ενός νέου μοντέλου υπολογισμού της διαμέτρου το οποίο βασίζεται στους κύριους παράγοντες που επηρεάζουν το μέγεθός της, δηλαδή στις παραμέτρους εκτέλεσης του Jet Grouting, την αξιολόγηση και σύγκριση των μεθόδων μέτρησης της διαμέτρου των εδαφοπασσάλων καθώς και με προτάσεις για την αξιολόγηση της αντοχής των δειγμάτων. Επίσης πραγματοποιείται η ανάπτυξη ενός νέου μοντέλου υπολογισμού της διαμέτρου το οποίο βασίζεται στους κύριους παράγοντες που επηρεάζουν το μέγεθός της, δηλαδή στις παραμέτρους εκτέλεσης του Jet Grouting, σε επί τόπου μετρήσεις στο εργοτάξιο, στον διαθέσιμο εξοπλισμό, στην πυκνότητα του ενέσματος και στις εδαφικές συνθήκες. Τέλος σημειώνεται ότι πέρα από το επιστημονικό υπόβαθρο, η παρούσα διπλωματική εργασία αποτελεί ένα πρακτικό εργαλείο και βοήθημα σε κάθε Γεωτεχνικό Μηχανικό που προβλέπει στη βέλτιστη εφαρμογή της μεθόδου Jet Grouting.
Acknowledgements

My deep appreciation to my Supervisor Dr. Jamie Standing, Senior Lecturer in Imperial College London in the Department of Civil and Environmental Engineering for providing me the opportunity to work with him. Jamie, many thanks for the interesting discussions in the College, the comments and corrections as well as for your invaluable support in the completion of the current thesis in a scientific way.

My greatest gratitude is expressed to my first Managing Director inside the Company that I am still active, Keller Hellas S.A., Dr. Thurner Robert. Robert, having almost completed one more step in Research fields and feeling the Jet Grouting beauty, I tried to find the right and proper words in English or in German or even more in my mother tongue Greek language to thank you; however, there are no words to express my real appreciation to you for your support in the execution and completion of this thesis; a thesis that started just as a ‘crazy’ idea a lovely evening of August in 2010 in Peraia by watching the ‘meeting’ of the sun with the Greek sea. You followed me step by step in this path even knowing that the working load could have given to me one million of arguments to stop the execution of this thesis; but it didn’t; many thanks again und bis nächstes Mal – ein guter Start wurde schon gemacht!!!

Many thanks to the whole ‘crazy’ team of Keller Hellas S.A. (Smon Wolfgang, George Kamenidis, Despina Topalidou, Marina Vacali and my operators George Arkoumanis, Tony Vagelopoulos and Kiri Antoniadis). My special gratitude is expressed to Despina for her contribution to be the current thesis as comprehensive as possible. The deepest appreciation belongs to George for his support in the data evaluation during the long and non-stop shifts in Thessaloniki. Thanks George and I hope to keep having the ‘eye of the tiger’ and the same working style, which you assigned, in my whole life!!

I also thank my Colleagues within Keller Grundbau. Mostly, I am grateful to my Sparteleiter, Mr Sigmund Christian for the interesting discussions. Christian, I promise that more trials/research will follow.

My appreciation to Mr Frank Ludwig, the best of the best of Keller Engineers in Jet Grouting field; his invaluable support in my Keller life and his willingness to support me any time are unbelievable, Vielen Dank Franki and I do expect a visit from you in Thessaloniki!!

I would also like to thank Mr Paul Marsden, Director of Keller UK in grouting techniques for his attitude to support me during my visits in London..

I feel a deep appreciation and I would like to thank my Foreman during my recent presence in Switzerland, Mr Lorenz Kleinerferchner, a person who was really next to me in every step, who became very quickly a good colleague and friend and gave me his invaluable support in the Jet Grouting ‘fights’ and never left me feeling alone!

Considering my Colleagues, last but not least, I have to express my great gratitude to the most patient person in my Keller life; my Foreman in Greece, Mr Geigl Helmut who is the one and only, a colleague and a friend, a person that follows my crazy ideas on sites and
shows extreme willingness to do more than his best in order me to apply new things in Jet Grouting and to get my ideas be done. Ein ganz grosses Danke Helmi!!

I have to thank also the main Contractor of the construction of Thessaloniki Metro, the Company AEGEK Constructions S.A., especially Mr Koutavas Nikos for the fruitful cooperation and also many thanks to the Engineers Mr Pilalidis Johnny, Mr Mplantas Thanos and Mr Aggelakis Lefteris and all the laboratory guys for the cooperation during the long shifts in ‘Analipseos’ Station.

Last but not least, I am grateful to my family and my friends for their understanding and support; especially I have to thank Mr Apsilidis Nikos for the interesting discussions in the research fields and his encouragement to me for keep believing in my thoughts. Many thanks also to my ‘old’ friend Mr Fotaroudis Dimitris who based on his deep knowledge in mathematics and applied statistics gave me invaluable support in the data analysis without taking into consideration what time my issues were set…..!!!! It’s nice to have good friends in this life!!!!
Terminology of Jet Grouting

- **Jet Grouting Method (JG):** ‘Jet Grouting technique is defined as a process of the disaggregation of the soil or weak rock and its mixing with, and partial replacement by, a cementing agent; the disaggregation is achieved by means of a high energy jet of a fluid which can be the cementing agent itself.’ (EN 12716, 2001)

- **Jet Grouting element:** the element which is constructed with the Jet Grouting method and consists of a mixture of grout/water/soil and any other additives that may be used during the application of the method.

- **Jet Grouting body:** one or usually more Jet Grouting elements that create a block of improved soil.

- **Drilling rods:** the rods that are adapted to the Jet Grouting rig in order to reach the required depth.

- **Jet Grouting Rig:** a drilling rig (usually with chains) in which drilling rods and other tools can be adapted for the proper execution of Jet Grouting works.

- **Nozzles:** the exit of the soil erosion fluid which comes out at high pressure.

- **Monitor:** A special tool which includes a certain number of nozzles and a drilling head.

- **Jet Grouting material:** ‘the material which constitutes the body of a jet grouted element.’ (EN 12716, 2001)

- **Lifting speed:** The rate of withdrawal of the monitor (thus of the drilling rods as well) during the jetting process.

- **Fresh-in-fresh sequence:** ‘the sequence of work in which the jet grouted elements are constructed successively without waiting for the grout to harden in the overlapping elements.’ (EN 12716, 2001)

- **Primary-secondary sequence:** ‘the sequence of work in which the execution of an overlapping element cannot commence before a specified hardening time or achievement of predetermined strength of the adjacent elements previously constructed.’ (EN 12716, 2001)

- **Prejetting:** ‘the method in which the jet grouting of an element is facilitated by a preliminary disaggregation phase, with a jet of water and/or other fluids. Prejetting is also known as prewashing or precutting.’ (EN 12716, 2001)

- **Spoil material:** mixture of grout-water-soil that comes to the surface through the annular space between the hole and the drilling rods during the Jet Grouting process.

- **Radius of influence:** ‘effective distance of disaggregation of soil by the jet, measured from the axis of the monitor.’ (EN 12716, 2001). The diameter can be similarly defined.

- **UCS:** Unconfined Compression Strength.
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1. Introduction

1.1 Inspirations/Motivations
Jet Grouting is a sophisticated method which was introduced to the field of geotechnical engineering more than 30 years ago; it primarily acts in the ground either as a mean of stabilization or as a sealing structure. With the aid of high pressure cutting jets of water or cement suspension, having a nozzle exit with a velocity ≥100 m/sec, sometimes air-shrouded, the soil around the borehole is eroded. The eroded soil is rearranged and mixed with the cement suspension. The result is a structured element ‘Soilcrete’ column, which has improved mechanical characteristics compared with the original soil.

Soil improvement by means of Jet Grouting is performed without possible visual inspection during the entire installation process; this is actually one of the beauties of the technique. In addition, despite the wide range of its applications and the large number of contractors in fields of geotechnical engineering, few companies acquire in reality the ‘know-how’ of the current technique. This issue, along with the fact that a Jet Grouting ‘marathon’ has been established for which a company will try to gain the competitive advantage, against its competitors, motivates geotechnical specialists to invest in research activities aspiring to the further development of Jet Grouting and enhance Jet Grouting performance and effectiveness.

The limited publications in crucial quality assurance issues of Jet Grouting such as the diameter control and the strength, along with the realistic spirit of competitively bidding in the ground engineering market, intrigued the author to investigate the ‘Pandora’s box’ processes involved with Jet Grouting. Currently, the financial crisis influences the already limited geotechnical European market. Notwithstanding, the author aspires to contribute to the further evolvement of the technique and to motivate all the stakeholders for a constant improvement in the field of Jet Grouting.

2. Jet Grouting – Overview

2.1 Types of Grouting and History of Jet Grouting
Grouting is generally used for voids filling in the ground with the aim to increase the soil resistance against deformation, to supply cohesion, shear-strength and uniaxial compressive strength or finally, to reduce the conductivity and interconnected porosity in an aquifer (Moseley & Kirsch, 2004).

‘Grouting for ground engineering can be subdivided into: permeation grouting, compaction grouting, hydro fracture grouting, jet-grouting, rock grouting, compensation grouting and deep mixing method’ (Kazemian & Huat, 2009). Jet Grouting is the technique analysed in the current thesis.
Regarding the history of the technique, according to Essler & Yoshida (2004), the earliest patent of Jet Grouting, was applied in England in the 1950s; nevertheless, its real practical development took place for the first time in Japan and it was first applied to create thin cut-off walls. In the early 1970s, rotating Jet Grouting emerged in Japan due to the fact that Jet Grouting panels could hardly create satisfactory products with varying thickness and fragile strength. In the mid-1970s, Jet Grouting was exported to Europe and since then, it has become popular worldwide. ‘In the 1980s, experience and confidence with Jet Grouting spanned a very wide range of application. Since the early 1990s, newer methods of Jet Grouting capable of a considerably larger columnar improvement have been developed on grounds of cost and programme’ (Essler & Yoshida, 2004). During the decade of the 2000s and also nowadays, the utilised equipment was constantly improved and played a significant role in the evolvement of the technique. Thus, higher pressures and flow rates were achieved and resulted in large diameters greater than 5 metres (China Papers, 2010) (Figure 1 depicts a 7 metre diameter soil improvement). Recently, the parameters of the nozzle’s upstream, such as the length and shape of the passage have been optimized in order to generate a more focused jet, in addition to the use of air (Yoshida, 2010).

Figure 1: 7 m diameter soil improvement (Burke, 2012)

2.2 Method Description-Background
Jet Grouting (or ‘Soilcrete’; this is very often used by Company Keller Grundbau as a term) is an eroding process and therefore both replacement and relaxation of the soil can occur during grouting. A Jet Grout body is constructed by injecting grout under high or low pressure into the soil through nozzles on a rotating drill string. The drilling rods are moved upward at a certain lifting speed; hence it creates a homogenous column of mixed grout and soil. By executing several columns which overlap, the strength and the stiffness of the soil are improved (see Figure 2).
In principle, Jet Grouting systems are classified into three major types depending on the number of fluids injected into the subsoil:

- **Single**: where grout is pumped through the rod and exits the nozzles of the monitor at high velocity (i.e. a minimum of 100m/sec). The energy of the grout stream simultaneously erodes the soil and replaces it with mixture of grout and soil.
- **Double**: where compressed air (2 to 10 bars) is added and surrounds the grouting in order to enhance the erosive effect.
- **Triple**: where the dissolution of the grain texture is achieved with a water jet with high pressure shrouded by an air jet for increased efficiency; the surrounding soils are hydraulically eroded and then are mixed with a jet of cement slurry in-situ; thus soilcrete columns are created. The cement slurry is injected with the same monitor from lower level nozzles, with the use of low pressure. In this grout filling process, due to the difference in the density, the grout mainly remains inside the Jet Grouting column whereas the water moves to the top. The excess water-soil-cement mixture flows to the surface through the annular space between drill rod and borehole wall.
The European Standard (EN 12716, 2001) suggests the following classification for the Jet Grouting systems:

- **3.4 single system**
  The jet grouting process in which the disaggregation and cementation of the soil are achieved by a high energy jet of a single fluid, usually cement grout.

- **3.5 double (air) system**
  The jet grouting process in which the disaggregation and the cementation of soil are achieved by one energy fluid (usually cement grout) assisted by an air shroud as a second fluid.

- **3.6 double (water) system**
  The jet grouting process in which the disaggregation of the soil is achieved by a high energy water jet and its cementing is simultaneously obtained by a separate grout jet.

- **3.7 triple system**
  The jet grouting process in which the disaggregation if the soil is achieved by a high energy water jet assisted by an air shroud, and its cementing is simultaneously obtained by a separate grout jet' (EN 12716, 2001).
2.3 Jet Grouting parameters

The determination of Jet Grouting quality is mainly based on experience that correlates a certain set of Jet Grouting parameters with various soil types; the final ground improvement (product of Jet Grouting) and its characteristics vary in different countries regardless of whether the same parameters were utilised. When Jet Grouting parameters are stated, they usually relate to the following technical features which in principle are 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 rig rods during the jetting process
- Type of Monitor and number or nozzles
- Rotations of the Monitor

The abovementioned parameters vary depending on the type of soil, the equipment used and on the special requirements of each project. The ranges that the Standard (EN 12716, 2001) suggests are just indicative and are given in the following Table 1:

<table>
<thead>
<tr>
<th>Jet grouting parameters</th>
<th>Single fluid</th>
<th>Double fluid (air)</th>
<th>Double fluid (water)</th>
<th>Triple fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grout pressure (MPa)</td>
<td>30 to 50</td>
<td>50 to 200</td>
<td>&gt; 2</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Grout flow rate (l/min)</td>
<td>50 to 450</td>
<td>50 to 60</td>
<td>50 to 150</td>
<td>50 to 150</td>
</tr>
<tr>
<td>Water pressure (MPa)</td>
<td>N/A</td>
<td>N/A</td>
<td>30 to 60</td>
<td>30 to 60</td>
</tr>
<tr>
<td>Water flow rate (l/min)</td>
<td>N/A</td>
<td>N/A</td>
<td>50 to 150</td>
<td>50 to 150</td>
</tr>
<tr>
<td>Air pressure (MPa)</td>
<td>N/A</td>
<td>0.2 to 1.7</td>
<td>N/A</td>
<td>0.2 to 1.7</td>
</tr>
<tr>
<td>Air flow rate (m³/min)</td>
<td>N/A</td>
<td>3 to 12</td>
<td>N/A</td>
<td>3 to 12</td>
</tr>
<tr>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The disaggregating effect is obtained by the high velocity of the jet, mainly dependent on the pressure of the fluid used for the disaggregation: grout in single and double (air) fluid systems, water in double (water) and triple fluid systems.

For single and double (air) fluid systems, grout pressure usually ranges between 30 MPa and 50 MPa, as defined in the table above. Lower limits down to 10 MPa have also been adopted in particular cases, such as small diameter jet grouted columns in very loose soils.

NOTE: The most recent developments in pumping equipment enable the pressure of the disaggregating fluid to reach up to 70 MPa or flow rates up to 650 l/min.

Table 1: Jet Grouting parameter ranges (EN 12716, 2001)
In the geotechnical environment and global market, the executional Jet Grouting parameters are constantly updated and depend also on the experience of the Engineers that deal with the technique. Burke (2004) proposes the ranges of values given in Table 2:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single Fluid</th>
<th>Double Fluid</th>
<th>Triple Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Pressure (bar) na</td>
<td>na</td>
<td>300 – 400</td>
</tr>
<tr>
<td></td>
<td>Volume (l/min) na</td>
<td>na</td>
<td>80 – 200</td>
</tr>
<tr>
<td></td>
<td>No. Nozzles na</td>
<td>na</td>
<td>1 – 2</td>
</tr>
<tr>
<td></td>
<td>Nozzle Sizes (mm) na</td>
<td>Na</td>
<td>1.5 – 3.0</td>
</tr>
<tr>
<td>Air</td>
<td>Pressure (bar) na</td>
<td>7 – 15</td>
<td>7 – 15</td>
</tr>
<tr>
<td></td>
<td>Volume (m³/min) na</td>
<td>8 – 30</td>
<td>4 – 15</td>
</tr>
<tr>
<td>Grout Slurry</td>
<td>Pressure (bar) 400 – 700</td>
<td>300 – 700</td>
<td>7 – 100</td>
</tr>
<tr>
<td></td>
<td>Volume (l/min) 100 – 300</td>
<td>100 – 600</td>
<td>120 – 200</td>
</tr>
<tr>
<td></td>
<td>Density (G) 1.25 – 1.6</td>
<td>1.25 – 1.8</td>
<td>1.5 – 2.0</td>
</tr>
<tr>
<td></td>
<td>No. Nozzles 1 – 6</td>
<td>1 – 2</td>
<td>1 – 3</td>
</tr>
<tr>
<td></td>
<td>Nozzle Sizes (mm) 1.0 – 4</td>
<td>2 – 7</td>
<td>5 – 10</td>
</tr>
<tr>
<td>Lift</td>
<td>Step Height (cm) 0.5 – 60</td>
<td>2.5 – 40</td>
<td>2 – 5</td>
</tr>
<tr>
<td></td>
<td>Step Time (sec) 4 – 30</td>
<td>4 – 30</td>
<td>4 – 20</td>
</tr>
<tr>
<td>Rotation</td>
<td>Speed (rpm) 7 – 20</td>
<td>2 – 20</td>
<td>7 – 15</td>
</tr>
</tbody>
</table>

Table 2: Jet Grouting parameter ranges (Burke, 2004)

Among various developments in the field of Jet Grouting, improvements are constantly achieved in the market; such innovations are the use of ‘Super Jet Grouting’ where the monitor has been modified and the outcome was an increase in the energy of the grout stream that erodes the ground (hence larger diameters, Figure 4), or the collided jetting (or ‘crossjet’ grouting, Figure 5) which results in columns with well-defined geometry. Finally, it is noted that instead of grout, bentonite or stone mill can be alternatively used depending on the project requirements.

Figure 4: Super Jet Columns (Burke, 2004)

Figure 5: X jetting (Burke, 2004)
The author, based on his own experience in Jet Grouting, presents a current updated version of the ranges of Jet Grouting executional parameters that can be applied. It is important to mention that the ranges in Table 3 are indicative and can be modified based on project requirements and the availability of the Jet Grouting equipment.

<table>
<thead>
<tr>
<th>Jet Grouting main components</th>
<th>Jet Grouting Parameters</th>
<th>Units</th>
<th>Single</th>
<th>Double</th>
<th>Triple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grout</td>
<td>Pressure</td>
<td>bar</td>
<td>400-450</td>
<td>400-450</td>
<td>50-90</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>lit/min</td>
<td>360-440</td>
<td>360-440</td>
<td>160-210</td>
</tr>
<tr>
<td></td>
<td>w/c</td>
<td></td>
<td>0,8-1,3</td>
<td>0,8-1,3</td>
<td>0,5-0,6</td>
</tr>
<tr>
<td></td>
<td>No of Nozzles</td>
<td>mm</td>
<td>1-2</td>
<td>1-2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Nozzles Diameter</td>
<td>mm</td>
<td>4,0-6,5</td>
<td>4-6,5</td>
<td>7,0-15,0</td>
</tr>
<tr>
<td>Water</td>
<td>Pressure</td>
<td>bar</td>
<td>-</td>
<td>-</td>
<td>300-350</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>lit/min</td>
<td>-</td>
<td>-</td>
<td>400-450</td>
</tr>
<tr>
<td></td>
<td>No of Nozzles</td>
<td>mm</td>
<td>-</td>
<td>-</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td>Nozzles Diameter</td>
<td>mm</td>
<td>-</td>
<td>-</td>
<td>4,0-6,5</td>
</tr>
<tr>
<td>Air</td>
<td>Pressure</td>
<td>bar</td>
<td>-</td>
<td>4-12</td>
<td>4-12</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>m³/min</td>
<td>-</td>
<td>5-18</td>
<td>5-18</td>
</tr>
<tr>
<td></td>
<td>Air ring</td>
<td>mm</td>
<td>-</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>No of Air rings</td>
<td>mm</td>
<td>-</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td>Lifting speed</td>
<td>cm/min</td>
<td>10-70</td>
<td>10-70</td>
<td>10-70</td>
</tr>
<tr>
<td></td>
<td>Rotations</td>
<td>rpm</td>
<td>2-20</td>
<td>2-20</td>
<td>2-20</td>
</tr>
</tbody>
</table>

Table 3: Jet Grouting – Ranges of the executional parameters

Considering the Jet Grouting systems that the author classifies, the following are stated:

- Single;
  - In this case, the only fluid that is used is the grout in high pressure.
- Double;
  - Use of air (low pressure 2 to 10 bars depending on the soil) and grout in high pressure. It is perfectly applied in sandy and gravel soils where the shrouded air assists in the construction of larger diameters than the ‘single’ system.
  - Use of water (in the air channel). This system is primarily applied in clayey and silty soils. Therefore, instead of air, water can be used in the air channel (10 to 30 lit/min) in order to avoid blocking of the monitor's nozzles. When this system
is applied, the strength of the treated soil has to be checked, in case the additional water has influenced the quality of the final product. According to the author’s experience, this additional water does not influence the strength of the treated ground. In addition, in contrast to the use of air, in this case, the diameter of column does not significantly increase.

**Triple**
- Cutting with water and filling with grout in one step.
- Pre-cutting where in the first stage, the soil is eroded with high water pressure; then the monitor is driven again down to the required depth and the Jet Grouting element is jetted with high grout pressure.

### 2.4 Jet Grouting applications

In contrast with conventional ground stabilization and improvement methods Jet Grouting can be also used for sealing of all kinds of soil ranging from loose sediments to clay (Figure 6).

![Application limits for grouting techniques](image)

*Figure 6: Jet Grouting applications in various soil conditions (Soilcrete, n.d.)*

This applies also for non-homogeneous soil, formations and changing soil layers, including organic material. Soft rock formations have also been treated and in addition, soils with grain sizes of up to 300mm (i.e. boulders) were successfully improved (Racansky, 2008).

Considering stabilization, underpinning works for adjacent construction pits is one of the main tasks of Jet Grouting; followed by foundation modifications and historical building foundation improvement. Shaft support, tunnel protection, deep foundations, earth pressure...
relief and horizontal applications can also be included in the wide range of Jet Grouting projects.

Regarding sealing works, Jet Grouting is applied in panel wall projects, dam sealing, in slabs which enables the execution of deep building pits without the need for large scale ground water lowering.

Finally, as far as limitations of the method are concerned, they are primarily governed by the fact that the surrounding soil must be eroded by the jetting stream. The resistance of the soil to jetting effects is nearly exclusively dependent on the strength of the untreated soil. In fine grain soils, the strength is correlated to the plasticity index; in practice, clays of semi-solid consistency can be successfully treated. In coarse grain soil conditions, the strength is governed by a density index; up to dense compaction, the method can be effectively applied. In the case of ground water flow, the speed of flowing water can reach substantial values and this can negatively affect the constructed element and its geometry (Racansky, 2008).

The author suggests that apart from the soil conditions which are evaluated and analysed before the commencement of any project, the proper execution of Jet Grouting is correlated with the specifications and the project requirements (such as time schedule, quality control, final product characteristics and properties, and budget) and what in the end can be achieved in terms of diameter and strength. For instance, at the appraisal phase of a project, a Jet Grouting solution can be an attractive one based on several assumptions; if a certain diameter can be achieved but the strength cannot meet the design requirements and the cost of cement does not make the improvement financially attractive anymore, then the Project Manager has to re-evaluate the case. Therefore, the project optimization and the characteristics of the final product (mechanical and geometrical) remain the crucial factors for the application of the technique.

2.5 Quality Issues

2.5.1 Diameter Control

One of the main issues of the current research is the estimation of the diameter that is created with the Jet Grouting process.

Despite the different methods that have been developed for the identification of the achieved diameter, this issue still remains vague and is often an open issue for discussion. The diameter control issue motivated and intrigued the author to investigate the methods available on the market, to analyse them and to evaluate them based on the literature and on his own experience, (i.e. in terms of reliability, application on sites, experience from old projects, uncertainties). The influence of soil parameters in the application of each method is also examined. Based on experience of executed projects and on in situ measurements, the accuracy of each method is checked using the various results and correlations between them developed. Some of the available methods for checking and the control of the Jet Grouting diameter that are analysed include:
1. Excavation.
2. Core drillings (vertical and inclined ones).
3. Thermic method, where measuring on site the temperature during the curing process of the binding agent (cement) in the centre of the Jet Grouting column, the achieved diameter and the cement quantity in the column can be calculated.
4. Jet Grouting column callipers; these are specific devices, which directly after the construction of the column, are lowered into the fresh Jet Grouting column, their arms opened and the diameter calculated.
5. Painted bars; they are installed vertically at depth around the column centre and at distances, approximately, equal to the expected column diameter. After the jetting process, they are removal from the ground and based on the erosion of their colour, the achieved diameter is assumed.
6. Hydrophones (the idea is similar to the painted bars methods).
7. Calculation model based on the specific weight of the mixed (grout and soil) material coming to the surface during the jetting process (spoil).
9. Wave Analysis Method; in this method the measurement and evaluation of the diameter of the Jet Grouting column are obtained based on the use of a wave analysis approach.
11. Analytical Approach and diameter calculation based on theoretical models.

2.5.2 Strength
Another crucial issue in the Jet Grouting technique is the strength of the final product. What is investigated are the factors, such as the water cement ratio of the utilised grout or the type of soil, that influence the strength. Apart from the available data in the literature, the author will present data from projects that he has involved with. In addition, the different ways that Jet Grout strength can be evaluated based on norms and standards are analysed. In practice, the strength is estimated either from unconfined compression tests on samples taken from of the backflow material or from cores that were obtained after a minimum of 28 days after construction. Another method which is not commonly used, the wet sampling process where a sampler installed on at the Jet Grouting rig, is driven down in to the fresh soilcrete column to retrieve material from inside the column, is also analysed.

2.5.3 Necessity of a Jet Grouting trial field
There is always an element of uncertainty with the Jet Grouting technique regarding quality control on site. This is in reality the main issue for every Contractor. The executional valid Standard for Jet Grouting is the EN12716 which provides various suggestions, recommendations and requirements for a proper quality control. Nevertheless, it is also mentioned in EN12716, that the execution of a field trial prior to the main works is an appropriate solution to establish the Jet Grouting parameters, to check the diameter measurements and any energy correlations and finally to assess the quality of the treated soil. It is the kind of investment for any project which requires a certain executional and
financial effort but it is strongly recommended especially in cases where there is no real experience of Jet Grouting works in the surrounding area. The field test still should not replace quality checks during execution; indeed, it serves as a tool to estimate in advance more precisely at the design phase the construction costs (Saurer, et al., 2011).

Hence, prior to starting production in a jet grouting project, a field trial programme is typically undertaken for the evaluation and refinement of the injection parameters and also the assessment of the jet grout element considering geometric, mechanical and permeability properties (Schorr, et al., 2007), (G&P, 2007). Stark, (2009) supports the current thinking and states in a more sophisticated way that ‘clearly, Jet Grouting is more technically demanding and less forgiving, than perhaps other ground improvement methodologies’. Thus the more information that is available before the commencement of a project, the better the quality of the final product. Figure 7 shows excavated Jet Grouting columns subsequently coming from a comprehensive trial for a project in USA. The diameter achieved is clearly depicted.

Figure 7: ‘Experimental jet-grouting columns’ (Malinin, et al., 2010)

Generally the test programme and its results are observed, reviewed and approved by the Engineer. The test programme should be installed in areas near the planned production work at a location agreed upon between the Engineer and jet grouting subcontractor and in representative soils and depths anticipated to be found during production work (ASCE, 2009).
2.5.4 Soil Inclusions in the Jet Grouting body
As has been previously described, the technique of Jet Grouting utilizes high pressure/velocity jet fluids to erode the existing soil and then the cuttings are mixed with the cement slurry, thus forming a soilcrete body. The application of Jet Grouting in a large variety of projects has proved that in the case where the native soil is not properly mixed with the slurry, the Jet Grouting elements produced will include soil inclusions within their body (Figure 8). This fact does not really influence the efficiency of the method; indeed, it is the kind of information that the Geotechnical Designer has to take into consideration during the appraisal phase of the project. Whenever the soil is not properly mixed with the grout and native soil (or even voids) remains inside the column, then the strength of the Jet Grouting body can be reduced while the permeability may be increased. It has also been noted that the amount of the soil inclusions can be established only by excavation and not by coring (Stark, 2009). Finally, the presence of soil inclusions in the Jet Grouting body depends on the type of in-situ soil and its characteristics and also the diameter that is finally achieved.

Figure 8: Picture where 50 to 60% of the interior of the Jet Grouting column is soil, column diameter 3 m, (Stark, 2009)
3. Diameter Control

3.1 Introduction

Estimating the diameter of a constructed Jet Grouting element is not an easy and simple task; taking into consideration the soil risk (possible variations even in a homogenous ground layer) which cannot be purely mitigated, the validation of the Jet Grouting diameter still remains an issue. There are many factors that influence the size of the final diameter that is constructed; the most important are:

- the ground erosion ability,
- the type of soil and its strength,
- the operating parameters of the Jet Grouting process (such as the lifting speed, grout or water pressure),
- the available Jet Grouting equipment (high pressure pumps, available monitors and rig) and
- the variations in the technique (single, double, triple).

Various methods have been used and proposed and intense research has been carried out. The diameter control issue intrigued the author to investigate the methods available on the market, to analyse them and to evaluate them based on the literature and on his own experience (reliability, application on sites, experience from old projects, uncertainties). Figures 9 and 10 present exposed columns from different cases where different shapes are presented; it is obvious that the estimation of the diameter is not a simple task.

3.2 Jet Grouting Diameter Control Methods

Soil improvement by means of Jet Grouting is performed without possible visual inspection during the entire installation process; this fact motivates the people involved in Jet Grouting projects to find innovative solutions for the estimation of the geometrical characteristics of
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

The treated soil. The methods available on the market can be categorised in three main groups:

- Those where visual inspection takes place, (for instance exposed columns, Figures 9 and 10),
- others where no visual check is possible or is not required and lastly,
- those where the diameter is calculated based on theoretical approaches.

In the second category, the quality control is enabled without being time consuming and is carried out during or just after the soil treatment. The third category involves models that are in principle based on theory; such analyses are usually done independently of site measurements.

3.2.1 Jet Grouting Diameter Control – Methods based on visual inspection

Excavation

The most appropriate technique is to construct trial columns, to excavate and to expose them so that the diameter can be measured directly (Essler & Yoshida, 2004). It is the most accurate method, but it can be only used at shallow depths or on sites where the local conditions (existing buildings, limited working space etc.) allow such works. Generally, it is better to excavate Jet Grouting elements that are not in contact or overlapped with other columns. In this way, it is easier not only to measure precisely the diameter, but also to check the shape of the constructed element. This is a very important topic in the design phase and it should not be forgotten that a Jet Grouting element is not a cased pile but part of ground improvement works and its shape is related to the strength of the surrounding in-situ soil (example are presented Figures 11, 12 and 13). Nevertheless, excavation of Jet Grouting columns is in most cases a time consuming and expensive solution.

Figure 11 & Figure 12: Jet Grouting columns exposed after excavation (left side: Retaining works in the construction of an Office Centre project in Greece, right side: Thessaloniki Metro, Analipseos Station -15 m).
Coring
Since Jet Grouting started to be used in geotechnical projects, excavation is still considered to be the most reliable method of determining the achieved diameter. However, as has been mentioned, for various reasons, this is not always feasible. Another reliable way to estimate the diameter is the core drilling method. In this case, there are two options for the geotechnical contractor; either to execute two or more vertical core drillings or one or two inclined ones. In both cases, the appropriate equipment and experienced personnel are required. For instance, when the drilling head reaches the Jet Grouting body, the drilling operator must change the drilling bit and continue with a diamond drilling head. A core, when it is in good quality can give valuable information about the constructed diameter, the type of soil (Figure 14) and can also be utilised for unconfined compression tests. Considering the fact that core drilling is a time-consuming method and at its executional phase, the project time schedule is usually very tight, the quality of the core has to be as good as possible. An accurate result can only be achieved if the deviation of the core drilling can be measured.

Figure 13: Exposed Jet Grouting column – Diameter 2.6 m in Tribuna Project (Ljubljana)
When the core is removed, there are several steps that the Engineer should follow in order to calculate accurately the diameter of the element. The information required is as follows:

- Deviation of the column itself and the deviation of the core drilling at the same axis system and in many levels depending on the column length.
- Coordinates of the drilling point of the column and the coring at the surface.
- Length of the core sample and of the column (Figure 15).
- Angle of the executed core drilling in the case that it is inclined.

Using basic formula from geometry, the diameter can be calculated. Figure 16 depicts perfectly the end of a core and can be also seen the 30 degrees of the angle that the core drilling was carried out. The author, based on his experience on sites and having determined the diameters produced using the coring method, strongly recommends its use and especially the inclined type; the effort is much less than in the case of vertical core drillings since the diameter estimation requires more than one vertical cores and there is always the danger that the drilling bit will be deviated outside the Jet Grouting body. Notwithstanding, even in the case of inclined core drillings, there are still risks that have to be mitigated. Figures 17 and 18 clearly depict the case. It is crucial to have information of the different soil strata; it is possible a different set of Jet Grouting parameters (such as lifting speed or pressure or flow rate) need to be adopted for different soil conditions. Particular care is
needed in inhomogeneous ground conditions. In such cases, two core drillings are required for the estimation of the average diameter since core sample A has a smaller diameter than the B one.

Figure 15: Core samples (inclined coring) for defining the achieved diameter (Thessaloniki Metro – Analipeos Station)

Figure 16: Core sample where the end of the core is perfectly depicted (Thessaloniki Metro – Trial field)
‘The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.’

Figure 17: Different diameters in the same column – Coring process

Figure 18: Jet Grouting column – Plan view in 2 different levels
3.2.2 Jet Grouting Diameter Measurement – Methods without visual control

Thermic method (based on in-situ temperature measurements)
In the last decade, a new concept has been introduced to the market by Dr. Meinhard (Meinhard, et al., 2007) regarding the identification of the diameter of the Jet Grouting and the cement content that is included in the body. Both are the major issues regarding the dimensions and properties of a Jet Grouting element and the most important for the geotechnical designer.

Following from the work presented by Brandstätter (Brandstätter, et al., 2002), this new method exploits the exothermal characteristics during the hydration process of early-age jet grouted soil (Brandstätter, et al., 2005). In addition, another important issue of this method is the thermal properties of the native soil and the Jet Grouting body itself.

With regard to the simulation of the hydration process, the properties (e.g. mineralogy, blaine value) of the employed binder (in most cases cement) are considered within a multiphase hydration model for Ordinary Portland Cement (OPC), which is extended towards blended cements (OPC mixed with blast furnace slag, lime stone) and validated by means of differential calorimetric tests.

Considering the thermal problem, the analyses done, showed that the temperature history measured on site, especially after having reached the maximum value, is strongly influenced by the thermal properties of the in-situ soil, i.e., the heat capacity and thermal conductivity (Meinhard, et al., 2010). Hence, for the solution of the thermal problem, the volumetric heat capacity C [kJ/(m³K)] and the thermal conductivity k [kJ/(mhK)] of the Jet Grouting mass as well as the in-situ soil are required. In order to account for the large range of these properties in granular, dry to fully saturated material, the determination of C and k from the properties of the individual material phases, such as particles, water, and air is proposed (Meinhard, et al., 2010). In addition to models given in the literature for dry and saturated cases, a model based on finite element analysis is employed in order to determine the thermal conductivity in the range of low and high values for the degree of saturation. Regarding the Jet Grouting mass, the influence of the column diameter and the cement content on the temperature history at the centre of a Jet Grouting element requires, in a first stage, a numerical study. The geometric dimensions of Jet Grouting columns in most applications (except e.g. sealing slabs) are characterised by L/D>1, where L and D denote the length and the diameter of the column, respectively. Hence, according to Meinhard et. al. (2010), the three-dimensional thermochemical problem can be reduced to a plane model considering only the cross section of the column. Hereby, the temperature flow in the longitudinal direction of the column is set equal to zero. Moreover, the axisymmetry of the cross section of the Jet Grouting element allows a further reduction in the numerical model to a one-dimensional axisymmetric model. The latter is solved by means of the finite element method (FEM).

Summarising, the thermic method is based on temperature measurements of the binding agent (in most cases cement) at the center of a Jet Grouting column directly after its
construction; the measurements have a minimum duration of 30 hours and are recorded by data loggers. The temperature history in the center of the column measured on site is reproduced by numerical simulations adapting the columns diameter and the cement content of the improved soil in a numerical model. The temperature measurements are loaded into software and a temperature curve is calculated correlated with the time (in-situ curve). This in-situ curve is compared with the theoretical model curves from finite element analyses, produced for the various types of binding agents (cement) used in the construction of columns. The finite element curve (FE-Model curve) that best fits with the in-situ one is established using a software package. Then, it is estimated the achieved diameter and the cement quantity in the column (Diagram 1).

It is mentioned that there is always only one theoretical curve that fits with the in-situ one and proves the diameter (for instance D=155 cm) and the amount of cement inside the Jet Grouting body (for example 490 kg/m³ of Jet Grouting) (Diagram 1).

In the thermic model, presented above, the input parameters in the developed software package are:
- In-situ temperature measurements at the centre of the column,
- the properties of the employed binder (usually cement) validated by calometric tests,
- thermal properties of the surrounding soil; (the soil temperature and the specific weight (dry and saturated) values of the ground in the software tool; then through a Finite Element Method model, it is calculated the volumetric heat capacity $C$ [kJ/(m³K)] and the thermal conductivity $k$ [kJ/(m·h·K)] of the in-situ soil).

The outputs (Diagram 1) in the developed software tool are:
- the diameter of the column,
- the cement content inside the Jet Grouted mass.

During the period of development (2005-2007), the tool developed was applied to more than 60 Jet Grouted elements at various construction sites (Meinhard, 2011).

In general, the author believes that the model provides promising results; the software tool is friendly and the results sheets are easy to understand and convenient for Site Engineers and Managers. Installing on site is straight forward and simple (Figures 19 and 20). Nevertheless there is still a lot of space for improvement. For instance:
- The multiphase hydration model developed for (blended) cement may be replaced by the single-phase hydration model (Meinhard, et al., 2010).
- There is uncertainty in the definition of the thermal properties of granular surrounding soil material and the determination of the proper thermal conductivity remains vague.
- Ground water flow is another topic of ongoing research.
- Verification of the geometric dimensions of the Jet Grouting columns; this means that, in the certain level where the thermic sensors are installed and the temperature of the column is measured, it is not clear what exactly the model measures. Figure 21 illustrates this case.
Diagram 1: Output of the software tool of Porr when the calculation has been completed – Keller Hellas test field
Figure 19: Installation of the thermic pipe for in-situ measurements in city center (Thessaloniki Metro)

Figure 20: Preparation for temperature measurements (Thessaloniki Metro)
Jet Grouting column Keller Callipers
The company Keller Grundbau GmbH has developed a special system for measuring the diameter of Jet Grouting elements, directly after its construction by the use of a hydraulic caliper system (Figure 22). In the first instance, before any use, the device is calibrated on site (Figures 23 and 24); there are two hydraulic functions. The ‘arms’ are opened step by step and the measured values are noted on the calibration sheet. After calibration is completed, the callipers are closed again completely (Getec, 2004). After, the column has been constructed and the jetting monitor taken out, the calliper device is mounted at the base of the drilling rods and is driven down to the required depth within the fresh grouting element. To measure the diameter, the arms are rotated from a vertical to a horizontal position by a first hydraulic circuit and then the arms extend horizontally using of a second hydraulic circuit. The extension of the arms is measured by noting the change in the volume of a calibrated piston and as soon as pressure increase is detected, this is noted and is considered to be the edge of the column (Driesse, et al., 2008).
The device is most commonly used in cohesive types of soil; this limitation exists since when stones or gravel are present, there is a danger that the stones may block the arms during the closing procedure and the device cannot be withdrawn at the surface. In addition, large grain size gravel can also prevent the proper opening of the arms. When long Jet Grouting columns (more than 4 metres) have to be formed, it is better to execute the calliper measurements steps after every 3 metres have been constructed.
‘The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.’

Figure 23: Calibration of the callipers on site (London, Victoria Station, November 2011)

Figure 24: Callipers – Application on site after calibration (Thessaloniki Metro, April 2011)
Painted Bars
This method is very practical and is commonly used by many companies in the market. It can be easily applied on site and the whole concept is quite simple. In principle, steel bars (Figure 26) are painted and then they are installed with the aid of the drilling rig around the drilling point at specific distances (Figure 25).

The concept of the method suggests that the erosion of the painted bars defines if the grouting energy was adequate enough to erode the soil to the required distance. For instance, if a diameter of 120 cm has to be checked, painted bars/pipes can be installed at a distance of 50, 60 and 70 cm from the centre of the column (Figures 25, 27). Drilling takes place to the required depth, then the bars/pipes are installed from inside the drilling rods, the rods are removed and the painted bars remain in situ. Once, the column has been constructed and the grouting phase is complete, the bars are extracted and the erosion of their paint/colour is checked (Figure 28). The technique is recommended for depths up to approximately 10 to 15 m, since the extraction of the pipes (after the column has finished), becomes a risky and difficult task. Over than the above mentioned range of depths, especially in gravel in soils, it is also possible to hear and 'feel' the erosion of the bars as the gravel scrapes on the bars. Prerequisite for the proper application of the method is the measurement of the deviation of all the boreholes that are executed (column's centre point and those for the painted bars).

Figure 25: Illustration of the painted bars function
Figure 26: Painted bars prepared for installation

Figure 27: Painted bars at two different distances from the theoretical centre of the column (T-panels project – Thessaloniki Metro)
Hydrophones

This method was developed and patented by the Company Bilfinger Berger AG. The idea behind the method is quite similar to the painted bars technique. Steel bars with an approximate diameter of 4cm are installed and sealed around the drilling point (theoretical centre of the Jet Grouting element) at distances to which the Jet Grouting diameter is assumed to extend. The holes created are filled up with water. The hydrophones are specific devices (Figure 29) with sensors which are attached to the steel bars.
During the Jet Grouting process, whenever the monitor’s nozzle energy is at the elevation of the hydrophone, an electrical signal is sent to the device located at the ground surface (Figure 30). Evaluation of the signals received allows the achieved diameter to be calculated.

Figure 30: Equipment used for the application of the hydrophone method (Leible, 2011)
It is important to mention that the proper application of the current technique requires the measurements of the deviations of all the executed drilling holes; hence not only the one for the Jet Grouting element but also for the ones carried out for the installation of the steel bars and the hydrophones. Examples of the type of received signals and their evaluation include the following cases (taken from a German project where the method was applied):

a) **'No increase (peak) at all in the electrical signal'** (Figure 31): in this case, the energy that is released by the nozzles of the monitor is not large enough to reach the sensor that the hydrophone has; thus the distance between the centre of the column and the hydrophone is shorter than the designed radius and the diameter has not been achieved.

b) **'Table signal'** (Figure 32): in this case, it seems that the design diameter was achieved, but it is at the limit.

c) **'Waves signal'** (Figure 33): the design diameter has been reached.

d) **'Peak signal'** (Figure 34): there is a great focus of the grout energy to the hydrophone; meaning that the design diameter has been clearly achieved.

![Figure 31: No peak at all in the electrical signal – the design diameter was not achieved (Leible, 2011)](image1)

![Figure 32: Table signal – the design diameter was achieved (Leible, 2011)](image2)
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

Figure 33: Waves signal – the design diameter has been achieved (Leible, 2011)

Figure 34: Peak signal – the design diameter has been clearly achieved (Leible, 2011)

The Company Bilfinger Berger furthered its patent and developed a software where, after the evaluation of the hydrophone signals and the drilling deviations, the radius (hence the diameter) of the Jet Grouting element is illustrated in a 3D model in different depths (example shown in Figure 35). In Figure 36, the model application on site is depicted.
Figure 35: 3D illustration of the Jet Grouting element after the evaluation of the hydrophone method (Leible, 2011)

Figure 36: Application of the hydrophone method on site (Leible, 2011)
Measurement of the specific weight of the spoil material

As it also suggested in EN (12716, 2001), that the spoil material which is produced during the Jet Grouting process, i.e. the mixture of grout-water-soil that comes to the surface through the annular space between the hole and the drilling rods. In reality, the spoil consists of exactly the same ingredients as the Jet Grouting can be used to estimate the Jet Grouting column diameter grout-water-soil. Collecting data concerning the spoil material (density, strength, grain size distribution, viscosity, bleeding and other more) can be worthwhile for the project and its quality control. It is often considered a prerequisite for the proper application of Jet Grouting (Martak, 1999; Schubert, 2002). The method that is described in the current chapter deals with the spoil material and especially with its specific weight. It was developed by Michael Lesnik in the Technical University of Graz (Lesnik, 2003). In his thesis a theoretical model to determine the diameter of cylindrical jet grouted elements is developed. On the basis of a mass-balance formulation a correlation is established between the components of the inflow during the jet grouting process (cement and water), the eroded masses in the ground and the waste slurry respectively. Initially, the general idea of the model was based on the following formula (Lesnik, 2003):

$$D = \sqrt{\frac{Q_v \cdot (\rho_v - \rho_w)}{\frac{\pi}{4} \cdot v_z \cdot (\rho_w - \rho_s)}} \quad [3.1]$$

where:
- $D$: diameter of the Jet Grouting element (m);
- $Q_v$: the grout flow rate that is pumped into the soil (lit/min);
- $v_z$: the lifting speed of the monitor and the drilling rods (m/min);
- $\rho_w$: specific weight of the water saturated soil (g/cm$^3$);
- $\rho_s$: specific weight of the spoil material (g/cm$^3$);
- $\rho_v$: specific weight of the grout (g/cm$^3$).

Some researchers (e.g. Kluckert, 2000) cast doubt on the validity of the above formula along with its requirements and assumptions; Lesnik (2003) developed the model starting with the following formula:

$$m_v + m_{B,e} = m_{DS} + m_r \quad [3.2]$$ (Lesnik, 2003)

where:
- $m_v$: mass of injected grout (gr);
- $m_{B,e}$: mass of the eroded soil (gr);
- $m_{DS}$: mass of the Jet Grouting element (gr);
- $m_r$: mass of the spoil material (gr).

Several basic assumptions were taken into consideration before arriving at the final form of the current model:
- the soil has to be homogenous and saturated,
- the Jet Grouting element has a cylindrical shape,
- the water/cement ratio is the same in the Jet Grouting element and in the spoil material.

Lesnik (2003) concluded with the formula:

$$D = \frac{Q_v \cdot (\rho_v - \rho_r)}{\pi \cdot v_z \cdot (\rho_{DS} - \rho_B)}$$  \[3.3\]

Where,

- $\rho_{DS}$, the specific weight of the Jet Grouting element (g/cm$^3$);

It is obvious that equations [3.1] and [3.3] are very similar; the difference in [3.3] occurs in the involvement of the specific weight of Jet Grouting element. Lesnik (2003) improved his model by including certain soil characteristics, in the form of $d_{max,r}$ and $A_B$ factors; the former is related to the maximum soil grain size inside the spoil material and the latter to the percentage of the soil that is replaced by grout during the execution of the Jet Grouting process. Lesnik (2003) states that considering a viscosity of spoil of $\eta_r=0.02$ kg/m.s, the $d_{max,r}$ factor comes to a value of 3 to 6mm. Factor $A_B$, is defined as the ratio of the soil mass in the spoil material to the soil mass that is eroded during the Jet Grouting procedure. The value of $A_B$ varies depending on the soil conditions; Lesnik (2003) suggests table 4 regarding the proper value for $A_B$ factor for various soil types as shown in Table 4:
Table 4: Values of $A_B$ factor based on soil conditions

Having selected defined the appropriate $A_B$ factor (its calculation is more precise when the grain size distribution is available) and having measured on site the specific weight of the spoil material, the diameter of a Jet Grouting element can be calculated. The rest required inputs include the soil’s specific gravity value along with the density, the specific weight of cement, the flow rate of the grout, the water flow rate (if it is used), the lifting speed of the monitor and the water/cement ratio (see also Table 5).

It should be also noted that there are ranges of the input values in the current model in order to calculate values as accurate values as possible (Table 6). The model cannot be implemented for the triple system.
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Table 5: Input of the model (Lesnik, 2003)

The outcome of the before mentioned input is the table 7 where the diameter is calculated.
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

### Table 6: Ranges of the input values for Lesnik's model (Lesnik, 2003)

<table>
<thead>
<tr>
<th>Eingabeparameter</th>
<th>Einheit</th>
<th>Basiswert</th>
<th>min.</th>
<th>max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kornichte $\rho_s$</td>
<td>g/cm³</td>
<td>2,70</td>
<td>2,65</td>
<td>2,80</td>
</tr>
<tr>
<td>Trockendichte $\rho_d$</td>
<td>g/cm³</td>
<td>1,80</td>
<td>1,70</td>
<td>2,00</td>
</tr>
<tr>
<td>Bodenaustauschgrad $A_B$</td>
<td>[1]</td>
<td>0,50</td>
<td>0,20</td>
<td>0,90</td>
</tr>
<tr>
<td>förderbarer Bodenanteil $a$</td>
<td>[1]</td>
<td>0,70</td>
<td>0,20</td>
<td>1,00</td>
</tr>
<tr>
<td>Rückflussdichte $\rho_r$</td>
<td>g/cm³</td>
<td>1,75</td>
<td>1,65</td>
<td>1,95</td>
</tr>
<tr>
<td>Durchflussrate $Q_{sus}$</td>
<td>m³/min</td>
<td>0,20</td>
<td>0,10</td>
<td>0,40</td>
</tr>
<tr>
<td>Ziehgeschwindigkeit $v_s$</td>
<td>lifting speed</td>
<td>0,20</td>
<td>0,10</td>
<td>0,50</td>
</tr>
<tr>
<td>Wasserzementwert $W/Z_{sus}$</td>
<td>W/C</td>
<td>1,00</td>
<td>0,80</td>
<td>1,20</td>
</tr>
</tbody>
</table>

### Table 7: Calculation of the diameter of a Jet Grouting element based on Lesnik’s model (all the values are random and are used as an example) (Lesnik, 2003)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Jetting</th>
<th>Eroded</th>
<th>Spoil</th>
<th>JG Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zusammensetzung</td>
<td>Vorlauf</td>
<td>erodiert</td>
<td>Rückfluss</td>
<td>Säule</td>
</tr>
<tr>
<td>Wasser</td>
<td>[kg]</td>
<td>1134,1</td>
<td>400,2</td>
<td>888,1</td>
</tr>
<tr>
<td>Zement</td>
<td>[kg]</td>
<td>1134,1</td>
<td>656,4</td>
<td>477,7</td>
</tr>
<tr>
<td>Boden</td>
<td>[kg]</td>
<td>0,0</td>
<td>2161,0</td>
<td>1080,5</td>
</tr>
<tr>
<td>Summe Masse</td>
<td>[kg]</td>
<td>2268,3</td>
<td>2561,2</td>
<td>2625,0</td>
</tr>
<tr>
<td>Wasser</td>
<td>[l]</td>
<td>1134,1</td>
<td>400,2</td>
<td>888,1</td>
</tr>
<tr>
<td>Zement</td>
<td>[l]</td>
<td>365,9</td>
<td>211,8</td>
<td>154,1</td>
</tr>
<tr>
<td>Boden</td>
<td>[l]</td>
<td>0,0</td>
<td>800,4</td>
<td>400,2</td>
</tr>
<tr>
<td>Summe Volumen</td>
<td>[l]</td>
<td>1500,0</td>
<td>1200,6</td>
<td>1500,0</td>
</tr>
<tr>
<td>Dichte $\rho$</td>
<td>[g/cm³]</td>
<td>1,75</td>
<td>1,84</td>
<td></td>
</tr>
<tr>
<td>$W/Z$-Wert</td>
<td>(W/Z)</td>
<td>1,35</td>
<td>1,35</td>
<td></td>
</tr>
</tbody>
</table>

| Durchmesser $D$ | [m] | Diameter | 1,24 |

Thomas Kimpritis, Imperial College London – MPhil Thesis, September 2013 – Page 55
Electric cylinder method (Cyljet-Geophysical method)
This method refers to an application of the Electric Cylinder® Method that has been developed and patented. A measuring instrument, consisting of a tubular element, is installed in the ground within a borehole; electrodes are fitted to the element and an electric field is created. The electric monitoring field around the hole (Figure 37) takes the form of a cylinder 2m to 5m in diameter, depending on the electric resistivity of the ground and instrumentation system employed (Pierre, 2011).

![ figure37 ]

Figure 37: Electric monitoring field depending on the electric resistivity of the ground and instrumentation system employed (Pierre, 2011)

In the first phase, a reference borehole is made in the ground, close to the location where the Jet Grouting technique is to be applied. The measuring instrument (tube with adjusted electrodes on it – Figure 38) is installed and data created by the function of the electrodes are recorded in various depths. Thus, a database of the physical characteristics of the ground conditions in the area of interest is created. In the second phase, the Jet Grouting element is constructed; the column resistivity must be measured promptly once the Jet Grouting process has been completed. The best procedure involves the installation of a non-steel tube (for instance a PVC pipe) in the fresh body. If this is not possible, then drilling has to take place. In either case, the measurements have to be carried out as soon as possible and no later than one or two days since the accuracy of the model will be significantly influenced (Pierre, 2011). If a new borehole is drilled through the Jet Grouting body, then, the same measuring tube with the electrodes is installed inside the column. The length of the tube is equal to the length of the column. Afterwards, electrical measurements are taken and
a physical parameter is derived; the latter is associated with the diameter of the column at certain depths along with the surrounding portion of ground involved in the electric field created (Pierre, 2002). The third phase involves the interpretation of the data obtained (Figure 39) with the aid of special software (CYLCART®) for visualization, CYLMOD® for modelling, CYLINV® for optimization & inversion, (Pierre, 2011).

Figure 38: Tubular element with electrodes (Pierre, 2011)

It is stated that the deviations of all the executed boreholes have to be measured in order to assure the accuracy of the geometrical characteristics of the columns.
Wave Analysis Method

In this method the measurement and evaluation of the diameter of the Jet Grouting column are obtained based on the use of a wave analysis approach. The general principle of the system is based on the correlation of at least two interconnected elements (Figure 40). Geophone data are correlated with the diameter of the columns and the overlap area. At the beginning, one column (‘recording’ column) is constructed; thus, its modulus of elasticity will be different from the one that characterizes the soil itself. At a second phase (for instance a couple of days later), a second column (‘signal’ one) is produced. During the second step, ‘contrasting vibrations are generated by the jet grout at the overlapping zone of both the recording and signal columns’ (Schorr, et al., 2007). Those vibrations can be plotted according to the rotations of the drilling rods and the jet grout monitor.

‘Elongation and frequency vibrations result in the signal column according to the jet’s rotation and injection times. In connection with the respective times of these characteristic vibrations, the angle of the overlap can be determined’ (Schorr, et al., 2007). It is also mentioned that the in-situ measurements can give information for the subsoil layers. Figure 41 depicts a cross section of a ‘recording’ and a ‘signal’ column for the whole length of the element; the overlapping zone is also shown.
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The above mentioned vibration analysis illustrates the correlation between changes in frequency and elongation with time. Then, the outcome is a spectrogram (Figure 42) where...
the “hills and valleys’ are distinct within the sequence of frequency over time, according to the rotation time of the jet’ (Schorr, et al., 2007).

The ‘hills and valleys’ are distinct within the sequence of frequency over time, according to the rotation time of the jet’ (Schorr, et al., 2007).

Figure 42: Spectrogram of a trial field in Columbia, Ohio, Diameter=1,2 m (Schorr, et al., 2007)

The final stage of the presented model results in the estimation of the constructed diameter of a Jet Grouting element on site.

3.2.3 Jet Grouting Diameter Control – Theoretical Approaches

Turbulent Kinematic Flow Theory

Recently, another method has been proposed as applicable for the most type of soils; an approach which estimates the diameter of a Jet Grouting element based on the theory of turbulent kinematic flow (Wang, et al., 2012). The eroding ability of the jet fluid on soil is evaluated using an empirical equation according to the results of previous experimental investigations. Regarding the principles of the calculation approach, it is considered that during the jetting process where water or grout erodes the soil, there is a penetration distance produced in the soil; hence the diameter of the constructed element can be estimated from this penetration distance ‘xL’. According to Wang et. al (2012), there are mainly two theories to get the abovementioned penetration distance, the turbulent kinematic flow theory (related to the jetting fluid) and the soil erosion theory. Based on the turbulent kinematic flow theory, fluid with the velocity of v0, is jetted from a round nozzle and the flow region can be divided into two parts: the initial zone and the main zone (Figure 43). Wang et.
al., (2012) taking into consideration Figure 43 and formulas from other researchers, suggest the following equation:

\[ \frac{v_{x_{\text{max}}}}{v_0} = \alpha \frac{d_0}{x} \]

where ‘\(v_{x_{\text{max}}}\)’ is the maximum velocity of the fluid along the x direction, ‘\(v_0\)’ is the exit velocity of the fluid, ‘\(d_0\)’ the nozzle diameter, ‘\(x\)’ the distance of the nozzle and ‘\(\alpha\)’ is a constant parameter which is related to the characteristics of the fluid and the soil. Wang et al (2012) state that for a specific soil, when the fluid is jetted onto the surface of this soil, there can be a critical velocity ‘\(v_L\)’ for soil erosion and the following equation is valid:

\[ v_L = \eta \left( \frac{\eta}{p_{\text{atm}}} \right)^k \]

where ‘\(p_{\text{atm}}\)’ is the atmospheric pressure, ‘\(k\)’ a dimensional exponent equal to 0.5 (Dabbagh, et al., 2002) and ‘\(\eta\)’ is a characteristic velocity with a value equal to the critical velocity when the soil resistance is equal to the atmospheric pressure, related to the characteristic of the soil. It can be considered that when the maximum velocity of the fluid along the x-direction ‘\(v_{x_{\text{max}}}\)’ decreased to the critical velocity ‘\(v_L\)’ for a type of soil, then the soil cannot be eroded anymore (Wang, et al., 2012). Hence for ‘\(v_L\)’=’\(v_{x_{\text{max}}}\)’ and ‘\(x\)’=’\(x_L\)’, based on the above two equations, the ‘\(x_L\)’ is calculated which is the penetration distance and leads to the estimation of the diameter of the Jet Grouting element. Thus (due to \(v_0 = \frac{4Q}{M\pi d_o^2}\)):

**Figure 43: Free jet from a round nozzle (Wang, et al., 2012)**
'The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.'

\[ x_L = \frac{\alpha}{\eta} \frac{4Q}{M \pi d_0 \sqrt{q_u / p_{atm}}} \]

Where:
- \( Q \) is the grout flow rate of the fluid (m\(^3\)/min),
- \( M \) the number of the nozzles of the monitor,
- \( d_0 \), the diameter of the nozzles (m),
- \( \alpha/\eta=b \) is a factor that is defined below and is related to the soil conditions, (\( \eta \) factor, (m/s)),
- \( q_u \), the soil unconfined compression strength (kPa).

Considering the diameter of the drilling rods as \( D_0 \), the radius of the jet-grouted column \( R_J \) can be obtained by the following equation:

\[ R_J = \frac{D_0}{2} + x_L = \frac{D_0}{2} + \frac{\alpha}{\eta} \frac{4Q}{M \pi d_0 \sqrt{q_u / p_{atm}}} \]

And setting \( \alpha/\eta=b \), it is possible to calculate the diameter of the Jet Grouting element since the \( b \) factor varies for different soil conditions. Wang et. al. (2012) suggest the following values for the \( b \) factor estimation; for clayey soils \( b=1,2 \) to \( 2,0 \); for clayey silts \( b=0,75 \) to \( 1,4 \) and for sandy soils \( b=0,25 \) to \( 0,75 \).

**Analytical Approach of Evaluating the Jet Grouting diameter**

A new approach has been recently developed and is presented below. According to (Carnevale, et al., 2011), a mathematical model has been formulated based on field observations; this model ‘will enable the designers to make an estimate of the column diameter and its mechanical characteristics’ (Carnevale, 2011). The basics and concepts of the computer program developed, for the evaluation of principal issues of Jet Grouting such as the column diameter, have been derived by combining basic soil mechanics and fluid pressure distribution. Various formulas that were used have been corrected with coefficients derived from field observations made at several sites, where several Jet Grouting parameters have been measured. The main issues and concept for this method are stated below.

‘The diameter of the column is a function of: a) the available energy employed by the machine; b) the soil resistance: the stronger the soil is, the more energy is needed to produce a given column’ (Carnevale, et al., 2011). The injection of grout at high pressure creates soil erosion and the final outcome at the monitor’s level is a mix of water-soil-grout. Carnevale et. al. suggest that depending on the soil characteristics the above mixture has three different paths that can follow:

1) Remain in the monitors level and the Jet Grouting element is formed;
2) Is dispersed in the surrounding soil by permeation;
3) Coming up to the surface through the annular space between the hole and the drilling rods of the Jet Grouting rig (spoil material)

Based on the above, Carnevale et. al. state the following: ‘The pressure of the grout at the nozzle \( P_n \) decreases with the horizontal distance \( x \) from the nozzle. Erosion of the soil will continue till the pressure value is higher than soil resistance \( q_u \). The distance \( x \) where injection pressure is equal to soil resistance \( q_u \) is the erosion radius \( R_e \). At the end of the erosion the cylindrical cavity will expand under the acting pressure. The soil at the boundary of \( R_e \) is at failure, thus the plastic zone around \( R_e \) will contribute to increase the horizontal displacement \( \delta \). The column diameter can be calculated by the following formula:

\[
D_c = 2 \times (R_e + \delta)
\]  \[3.4\]

The horizontal displacement \( \delta \) can be evaluated according to the formulas that Chai et. al. (2005) suggest.

The model also includes a weight balance equation which has also to be valid for the accuracy of the model (see Figure 44):

\[
P_m + P_t - P_p = P_c + P_f + P_d
\]  \[3.5\]

**Figure 44: Volumes involved in the model**

Where:

- \( P_m \): weight of the injected grout,
- \( P_t \): weight of the treated soil,
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

- $P_p$: weight of soil in the perforated hole,
- $P_c$: weight of column,
- $P_r$: weight of spoil,
- $P_d$: dispersed mix weight.

The above equation [3.5] can be expressed in terms of volumes through the relative bulk unit weight. The term $P_p$ can be considered as a second order component; therefore it can be neglected (Carnevale, et al., 2011).

$$\gamma_m \cdot V_m (1 - \alpha - \beta) = \gamma_c \cdot \frac{\pi \cdot D_c^2}{4} - \gamma \cdot \frac{\pi}{4} \cdot \left[ (D_c - 2 \cdot \delta)^2 - D_p^2 \right] \quad [3.6]$$

Where:

$$\alpha = \frac{\gamma_r \cdot V_r}{\gamma_m \cdot V_m}, \quad \beta = \frac{\gamma_d \cdot V_d}{\gamma_m \cdot V_m} \quad [3.7]$$

and the disperse volume can be calculated as:

$$V_d = \frac{\pi \cdot k \cdot q_u}{\gamma_d} \cdot \Delta t \quad [3.7]$$

Where:

- $\gamma_d$: unit weight of the dispersed fluid (approximately equal to $\gamma_m$ due to possible segregation of the grout)
- $k$: soil permeability,
- $\Delta t$: time step

All the concepts and formulas mentioned above for this theoretical approach of the calculation of the Jet Grouting diameter have been organized in Excel spreadsheets by Carnevale et al (2011). In those excels (inputs are depicted in Figure 45 and the evaluation process in Table 8), the calculation includes the values of the following:

- $D_c$: column diameter,
- $V_r$: spoil volume,
- $V_d$: dispersed volume,
- $u_f$: hydraulic fracturing pressure,
- $p_c$: cavity pressure,
- $p_r$: spoil pressure,
- $\gamma_r$: spoil unit weight,
- $\gamma_c$: column unit weight.
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

Figure 45: Input of the model (Carnevale, et al., 2011)

Table 8: A summary of the evaluation process of the theoretical model of (Carnevale, et al., 2011)
4. Strength

4.1 Introduction
In most projects, the strength of Jet Grouting is checked through uniaxial compression tests (Figure 46); triaxial tests under confining pressure are very rarely carried out. In principle, especially in big projects, a Jet Grouting trial test is executed prior to the main works in order to define the strength that can be achieved. Once a set of data has been gathered, the characteristic and design values can be calculated and based on these the project design can be accomplished.

According to (Nikbakhtan & Ahangari, 2010), ‘specifications of Soilcrete (which means Jet Grouting) columns that are achieved from the jet grouting procedures from a diameter and strength point of view, depend on jet grouting parameters such as grout pressure, lifting speed, rotating speed, number and diameter of nozzles, cement /water ratio and specifications of local soil’.

In addition to these factors relating to the Jet Grouting processes, the author suggests other factors that influence the strength of a sample are the following:

- Type of soil;
- Cement content inside the sample;
- Grain size;
- Grout flow rate and water/cement ratio;
- Type of cement;
- Sampling technique, coring or wet sampling;
- Type of sample (cylindrical, cubic) and its dimensions.

Figure 46: Jet Grouting core sample, before and after the unconfined compression test. (Thessaloniki Metro)

In relation to strength, initially various issues have to be determined:
a] What are the values of greatest interest;
b] How are those values defined;
c] What kinds of samples have to be tested in order to gain the most appropriate data for evaluation;

Considering the first issue (a), the values of greatest interest are: the mean (or average) value of a certain data base, the characteristic value and the design value.

Regarding issue (b), the mean value needs no further elaboration about its meaning; it is the average value of a certain data base. The characteristic value \( f_{m,k} \) is defined, according to the new DIN 4093 (2012) ‘Design of ground improvement – Jet grouting, deep mixing or grouting’ (which has a replaced DIN 4093:1987-09), as the minimum value of the following criteria:

\[
\begin{align*}
& f_{m,k} \leq f_{m,\text{min}}, \text{ where } f_{m,\text{min}} \text{ is the minimum value of the examined data base.} \\
& f_{m,k} \leq \alpha \cdot f_{\text{mean}}, \text{ where } \alpha \text{ is a factor with the following values:} \\
& \quad \text{a) } \alpha = 0.6, \text{ when } f_{m,k} \leq 4 \text{ N/mm}^2, \\
& \quad \text{b) } \alpha = 0.75, \text{ when } f_{m,k} \geq 12 \text{ N/mm}^2, \\
& \quad \text{interpolation is performed if } 4 \text{ N/mm}^2 \leq f_{m,k} \leq 12 \text{ N/mm}^2, \\
& f_{m,k} \leq 10 \text{ N/mm}^2.
\end{align*}
\]

Finally, the design value, \( f_{m,d} \) which what in reality a Geotechnical Designer needs, is calculated based on the characteristic value with two other factors:

\[
f_{m,d} = 0.85 \cdot f_{m,k} / \gamma_m, \text{ where } \gamma_m \text{ a safety factor which is equal to 1.5 for BS-P and BS-T (persistent and transient) cases and 1.3 for accidental situations.}
\]

In relation to issue (c) is concerned, according to (DIN 4093, 2012), cylindrical samples with height to diameter ratio \( h/d=2 \) have to be tested.

### 4.2 Published Literature

The cement content of the treated soil essentially influences its strength. This issue has a direct consequence on costs and the trade-off between strength and project costs should be definitely taken into consideration when examining the optimization of a design (Racansky, 2008). Gallavresi (1992) presents the strength of a Jet Grouting body in correlation with cement content with in the improved soil (Diagram 2).
Sondermann and Kirsch (2001) state that when cement is used in Jet Grouting and the cement content inside the body remains approximately 150 to 400kg/m$^3$, the following values can be taken into consideration regarding the strength:

- In sand and gravel soils: $f_{mk}=1.0$ to 15.0 MPa
- In silt and clayey soils: $f_{mk}=0.5$ to 3.0 MPa

On the other hand, Stoel (2001), based on the ground conditions, suggests ranges of limits for different soil types (Table 9) for the Jet Grouting strength that a Designer should take into account.

Diagram 2: Strength as a function of cement content; average experimental data of typical JG treatments (Gallavresi, 1992)
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

Table 9: Limits suggested by (Stoel, 2001), as cited in (Racansky, 2008)

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Clay</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Silt</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Sand</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Gravel</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>

In the following sections and chapters the author elaborates on the current approaches for determining and assessing the strength ranges of average strength values and alternative options for strength determination based on Jet Grouting applications are suggested.

### 4.3 Jet Grouting Strength Issues - Methods for evaluation

#### 4.3.1 Core Samples

One method that is commonly used in the geotechnical industry to check the strength of the Jet Grouting body is to perform unconfined compressions tests on core samples. The test results are evaluated and the mean $f_{\text{mean}}$ and the characteristic $f_{m,k}$ strengths of the cores are estimated. What is crucial in this case is the use of the right equipment (for example see Figures 47, 48 and 49) in order the samples to be obtained in the best condition and without any cracks that could influence their compressive strength. The transport of the samples to the laboratory should also be taken into consideration.

Figure 47: Craelius Rig for collecting core samples

Figure 48: Drilling head
4.3.2 Wet Sampling

According this procedure, a sampler with openings (see Figure 50) is attached to the Jet Grouting rig, and driven down in to the fresh column. The openings are activated with the aid of a compressor, allowing material from inside the fresh Jet Grouting column to be collected. This method is not commonly used in the industry but is simple and cheap; therefore it is recommended by the author.

It should be stated that the current process is not able to be applied to projects where the ground includes coarse gravel since it can block the holes of the sampler and prevent material from being collected.

When the samples are required from near surface, they can be collected and poured in to cylindrical or cubic formers (Figure 51) and transported to the laboratory carefully.
Figure 50: Wet sampling sampler
Little data have been published regarding the wet sampling process. Durgunoglu et. al. (2002) present the UCS values of wet samples with time from a project in Turkey (Diagram 3). The mean value of the results is approximately 1MPa.

Diagram 3: Variation of compressive strength values of wet sampling with time, (Durgunoglu, et al., 2002)
4.4 Jet Grouting Strength and Modulus of Elasticity

Another important characteristic of Jet Grouting material is the elastic modulus $E_s$. In many Jet Grouting applications, the main index of a quality control programme that has to be verified on site is not the diameter of the element or the strength but $E_s$. For instance, in projects where the deformations of the Jet Grouting body (such as in strutting slabs) have to be determined, the elastic modulus is the crucial parameter. $E_s$ can be measured on site with pressuremeter tests or can be calculated from the strength of the Jet Grouting body using empirical formulas.

The pressuremeter test is an in-situ testing method used to achieve a quick measure of the in-situ stress-strain relationship of the soil. In principle, the pressuremeter test is performed by applying pressure to the sidewalls of a borehole and observing the corresponding deformation (Geotechdata, 2010).

The pressuremeter consists of two parts, the read-out unit which rests on the ground surface, and the probe that is inserted into the borehole (ground). The original Ménard-type pressuremeter was designed to be lowered into a preformed hole and to apply a uniform pressure to the borehole walls by means of inflatable flexible membrane. As the pressure increases, the borehole walls deform. The pressure is held constant for a given period and the increase in volume required for maintaining the constant pressure is recorded. A load-deformation diagram and soil characteristics can be deduced by measurement of the applied pressure and change in the volume of the expanding membrane.

The major difference between categories of pressuremeter lies in the method of installation of the instrument into the ground. Three main types of pressuremeters are:

- The borehole pressuremeter: The instrument is inserted into a preformed hole.
- The self-boring pressuremeter: The instrument is self-bored into the ground with the purpose of minimizing the soil disturbance caused by insertion.
- Displacement pressuremeters: The instrument is pushed into the ground from the base of a borehole. The soil displaced by the probe during insertion enters the body of instrument, reducing the disturbance to the surrounding soil.

There are different approaches to the interpretation of results and the determination of material properties from pressuremeter tests. In general, these approaches rely on either empirical correlations to allow measured values of pressure and displacement to be inserted directly into design equations, or on solving the boundary problem posed by the pressuremeter test.

Test standards available for pressuremeter interpretation are:

- BSI BS 5930 Code of practice for site investigations (Geotechdata, 2010)
5. Case Studies – Construction projects for the Thessaloniki Metro

5.1 Introduction
Various aspects of Jet Grouting theory, in particular the measurements of column diameter and strength, have been reported in the previous chapters. Several of these have been on was applied on working construction projects by the author. At two Jet Grouting sites, ‘Analipseos’ and ‘Patrikiou’ Station, (Figure 52) various methods for addressing the diameter control or the strength issues were applied. What follows is a description of these projects where data were constantly collected and analysed afterwards.

5.2 Thessaloniki Metro – Projects Description
A large variety of the compiled data was collected during the Jet Grouting applications that were included in the construction phases of Thessaloniki Metro (map in Figure 49). This project has not been completed yet and will involve more Jet Grouting sites in the near future. Some details regarding this project, which is the largest ongoing in the Balkan region, are given below.

In September 2003 the decision was made for this specific project to be constructed by means of National and European Union funds. On the basis of the invitation to tender, in June 2004, five Joint Ventures consisting of major Greek and foreign companies of the construction industry expressed their interest in participating in this tender. Its first phase was completed in November 2004.

Finally, the Joint Venture of AEGEK – IMPREGILO – ANSALDO T.S.F – SELI – ANSALDOBREDA was awarded the design and construction of Thessaloniki Metro (Basic Line) and the agreement was confirmed by the contract between the Contracting Joint Venture and Attiko Metro S.A. (Project Owner- Public Sector) on April 7th 2006. Construction of the project commenced at the end of June 2006. (Attiko Metro, n.d.)

The construction of Thessaloniki Metro should integrate state-of-the-art technology and the most demanding standards concerning both quality and operation, rendering it, thus, the most modern Metro System in the whole of Europe. The basic line is to include:

- 13 modern centre platform stations;
- 9.5 km of the basic line using two independent single track tunnels, constructed mostly (7.7 km) by means of two tunnel boring machines. The remaining section of the line should be constructed by the Cut and Cover method;
- 18 ultra-automatic and state-of-the-art trains, fully air-conditioned, which will be run without a train driver, with an attendant aboard the train;
- platform screen doors, which guarantee greater safety levels;

- A Depot in the ‘Pylea’ region covering a surface of 50,000 square metres. Within the framework of the same development plan, provision has been made for the development of underground parking facilities in Thessaloniki Metro network, their capacity being 3,700 places in total.

In June 2007, the first tunnel boring machine (TBM) was under preparation in order to be delivered to Greece (November 2007) and start the tunnel construction (Figures 53 and 54).

Figure 52: Map of Thessaloniki Metro Project (Basic Line – red line) (Attiko Metro, n.d.)

‘Analipseos’ and ‘Patrikiou’ Stations are pinpointed
‘The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.’

Figure 53: Preparation of the first TBM, June 2007. (Attiko Metro, n.d.)

Figure 54: TBM arrival in Thessaloniki, November 2007. (Attiko Metro, 2011)
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.'

The project faced and continues to face various constructional and design problems which caused delays in the programme. Additionally, the unavoidable archeological investigations also led to delays in the progress of the project. Notwithstanding, the TBM continued to with the construction of the tunnels (Figure 55 – entering the ‘Crossover Sintrivani’ Station – November 2009).

![Figure 55: Tunnel Boring Machines – entered ‘Crossover Sintrivani’ Station (Attiko Metro, 2011)](image)

The Jet Grouting issue arose in the project during the progress of the TBM and their approach to ‘Analipseos’ Station. The geotechnical issues that involved the application of the Jet Grouting technique are described below.

According to the approved geotechnical evaluation report (1S10CW180B401B, 2010) and contractor’s reference drawing number 1S10CW180B402A, the area of ‘Analipseos’ Station, has a complex soil profile, consisting of medium dense, light brown to brownish green, clayey/silty sands with gravel, with intercalations of medium dense, clayey/silty gravels with sand up to a depth of approximately 27m below the natural ground surface. In reality, the soil is a mixture of clay, sand, silt and some gravel with some alterations of either clay or sand.

Regarding the soil parameters in the station area, the following can be stated: $\gamma=22.5\, \text{kN/m}^3$, $\varphi'=30^\circ$, $c'=10\, \text{kPa}$, $E_s =30$ to $35\, \text{MPa}$, $k_r=3$ to $5\times10^{(2)}\, \text{cm/sec}$, $k_v=3$ to $5\times10^{(2)}\, \text{cm/sec}$. 
In addition, a range of unconfined compressive strength values, $q_u=110$ to $150$ kPa, was also given as input (average value) for the execution of the Jet Grouting works (1S10CW180B401B, 2010). However the application of the Jet Grouting method necessitated a more detailed and focused soil investigation and analysis of the ground conditions in the area of ‘Analipseos’ Station. Because of the complex geology, the plan view of the station was separated in to five geotechnical areas.

A general plan view of the Station is depicted in Figure 56; the first part of the project (which involved Jet Grouting works) required the construction of a Jet Grouting wall between the future constructions of the two tunnels. Due to the shape of the Station (just 14,8 metres width), the distance between the outer lines of both tunnels was less than 3 metres. The ground conditions revealed the necessity of a soil improved area between the two tunnels; this improvement had to be carried out before the TBM passed (Figure 56). The second part of project involved the construction of a Jet Grouting strutting slab beneath the foundation slab which was to be made from reinforced concrete. This solution was an optimization of the original design which previously included the installation of 2 rows of steel struts in order to allow excavation to take place faster and to speed up the completion of ‘Analipseos’ Station. Both projects along with the construction sequence are described in more details below.

Apart from ‘Analipsesos’ Station, similar geotechnical issues appeared at the next station along the line ‘Patrikiou’. At this Station, the construction of a Jet Grouting slab was required. In this thesis, only the executed trial field is analysed since the main works had not been started at the time of writing this report.
5.2.1 Jet Grouting trial field – ‘Analipseos’ Station

Regarding the Jet Grouting applications in ‘Analipseos’ Station, there were two majors considerations. First there are many blocks of flats and buildings located nearby the station area (Figure 57), and second there was no previous experience of Jet Grouting works in the soil conditions in Thessaloniki. It was therefore necessary to execute of a trial field at the station area. The scope of the trial was to define the Jet Grouting parameters and finalize the design, based on the results with particular regard to achievable diameters and strengths.

Therefore, a very intense and extensive quality control programme was adopted and carried out prior to the main works; twenty-two columns were constructed in the area of the station in order to obtain information for the application of the main Jet Grouting works in all the five geotechnical areas. In the end, the single system was considered to be the optimum method for this type of soil conditions. A large variation and adjustment in the Jet Grouting parameters was required before the confirmation of the proper values for the optimum execution of the Jet Grouting wall (project 1) and the Jet Grouting strutting slab (project 2 – shaft area) (Figure 56).

5.2.2 Jet Grouting Wall – ‘Analipseos’ Station

The detailed investigation of the conditions in ‘Analipseos’ Station showed that safe passage of the TBM’s required the improvement of the area between the two tunnels for 45 metres in the plan view. This necessity occurred since the distance between the tunnels would be less than 3 metres (Figure 56). In total 191 Jet Grouting elements were constructed to form a stable wall of Jet Grouting material between the tunnels.

A great executional interest challenge arose for part of the project as the presence of adjacent roads necessitated, 49 Jet Grouting columns being installed with inclinations in two directions (Figure 57).

Before the commencement of the works, a certain test programme was executed in order to define the parameters of the Jet Grouting technique (Jet Grouting system, grout pressure, flow rate, lifting speed of the monitor, rotations of the monitor per minute and the water cement ratio, the diameter of the columns and the required strength). A grid of columns with diameters of 1.3 and 1.0 metre was selected with a water cement ratio of 1.3 and the characteristic value for the strength was calculated to be 0.9 MPa based on new DIN 4093 criteria.

During the execution of the project, a detailed and extensive quality control programme was applied in order to ensure the safe passage of the TBM’s. The diameter of the Jet Grouting elements was confirmed using the thermic method (5 tests out of 130 Jet Grouting elements) and at a later stage the inclined core drilling method was implemented (5 core drillings through the Jet Grouting body). Regarding the strength, the characteristic value was checked by testing wet samples and cores. Moreover, for every 10th column, the drilling deviation was measured in order to check the actual orientation and position of the Jet Grouting elements. If the deviations in verticality were systematically more than 2%, then, the deviation measurements should be made for every column in order to check if additional
columns were needed. In addition to the JG control, a very sophisticated monitoring system was utilised regarding any potential settlements or heave in the neighboring buildings.

Figures 58 and 59 illustrate the construction sequence. Samples of the grout and the spoil material were daily tested: the tests included unconfined compression strength tests, measurements of the specific weight, bleed tests and the application of the marsh cone. The whole works were reported in a very detailed and official way, since for every single element, a production protocol was produced. Such protocol included advanced information about the drilling, jetting, column deviation, grout, wet and spoil sampling and rig records.
Figure 58: Jet Grouting Wall construction before the TBMs passing – Cross Section A-A (see Figure 56)
Figure 59: TBM's passing after the ground improvement by the JG method – Cross Section A-A (see Figure 56)
5.2.3 Jet Grouting Slab - Analipseos Station

In optimizing the design of ‘Analipseos’ Station and the time required for its construction (excavation phase) the construction of a Jet Grouting strutting slab beneath the foundation level was selected. This solution was intended to eliminate the deformations of the diaphragm walls and neighboring buildings during the excavation phase. Approximately 3000 Jet Grouting elements were required for the whole area. In a first phase, the Jet Grouting method was applied in the shaft area (Figure 56).

After the execution of the field trial, a further optimization was gained in the design by allowing 10% of soil mass inside the Jet Grouting body whose thickness was 2.5m.

The test programme confirmed the executional parameters (as in the case of the first part of the project 1); a rectangular grid of 1.0mx1.0m of columns with diameters of 1.3 metres was specified with a water cement value of 0.9 and the characteristic strength value was calculated to be 3.5 MPa based on the new DIN 4093 criteria.

During the execution of this project (Figure 60) an extensive quality control programme was applied as with the Jet Grouting wall case. However, in this case, the quality control was much more intense. The diameter of the Jet Grouting elements was confirmed using the thermic method and the coring method. Regarding the strength, the characteristic value was checked by testing wet samples and cores regularly (twice a week). Since the wet samples were obtained directing after the construction of the Jet Grouting elements, there was the opportunity to check the compression strength of the Jet Grouting body in an early phase, for instance at 7 days.

In addition, the drilling deviation was measured in every column in order to check on one hand the actual position of the Jet Grouting elements at the base level of the Jet Grouting slab and on the other hand the case for additional columns. Similarly to the Jet Grouting wall case, a very sophisticated monitoring system was utilised regarding the control of any potential settlements or heave of in the neighboring buildings.
Figure 60: Execution of the Jet Grouting strutting slab in the Shaft area

Figure 61 and Figure 62 illustrate the final situation after all works have been accomplished. The construction sequence included the following steps:

- Construction of the diaphragm wall elements;
- Execution of the Jet Grouting slab;
- Excavation and concreting of slabs (level -1, -2, -3);
- Excavation and concreting of the foundation slab;
- TBM entering the Station;
- Shaft excavation.

In addition, the grout and the spoil material were daily tested; the tests included unconfined compression strength tests, measurements of the specific weight, bleed tests and the application of the marsh cone. Finally, it is stated that the whole works were reported in a very detailed and official way, since for every single element, a production protocol was produced; such protocol included advanced information regarding the drilling, the jetting, the column deviation, the grout, wet and spoil sampling and the rig records.
Figure 61: Cross section B-B (see Figure 56) – Final situation
Figure 62: Shaft overview after the completion of the excavation (January 2013 – ‘Analipseos’ Station) – Thessaloniki Metro
5.2.4 Jet Grouting trial field - Patrikiou Station

As mentioned earlier, the same geotechnical issues that occurred in ‘Analipseos’ Station, were also applied at the next Station, ‘Patrikiou’. At this site, only the Jet Grouting strutting slab was required. Regarding the soil conditions, there is the presence of geotechnical unit named A1a which is encountered along the whole length of the Patrikiou Station and consists of very soft to firm, brown sandy clay and silt of low plasticity, with interlayers of loose to medium dense, brown-greenish clayey/silty sand with gravels and clayey/silty gravels with sand. The soil characteristics can be summarised by the following values: \( \gamma = 21.7 \text{ kN/m}^3 \), \( c' = 10 \text{ kPa} \), \( \varphi' = 29^\circ \), \( C_u = 60 \text{ kPa} \), \( E_s = 15 \text{ MPa} \), \( k_h = k_v = 10^{-2} \) to \( 8 \times 10^{-3} \) m/sec.

In some areas where the Jet Grouting works will be applied, there is also the geotechnical unit A1b which is found along the ‘Patrikiou’ Station under the geotechnical unit A1a. This geotechnical unit mainly consists of medium dense to dense clayey/silty gravels with sand with lower participation of loose to medium dense clayey/silty with gravels. The geotechnical design parameters of unit A1b formations are the following: \( \gamma = 22.2 \text{ kN/m}^3 \), \( c' = 0 \) to \( 5 \text{ kPa} \), \( \varphi' = 35^\circ \), \( E_s = 35 \text{ MPa} \), \( k_h = k_v = 10^{-2} \) – \( 8 \times 10^{-3} \) m/sec.

In addition, a range of unconfined compression strength values of \( q_u = 75 \) to \( 120 \text{ kPa} \) was also given as input (average value) for the whole station. (1S11CW401R912A, 2012)

The above description indicates that the ground conditions are similar to ‘Analipseos’ Station but slightly weaker. The detailed analysis of the ground of ‘Patrikiou’ Station resulted in being divided into separation of four geotechnical areas. Therefore, a new trial field (Figure 63) was designed and included the construction of 14 trial elements in order to specify the Jet Grouting parameters. In the end, similarly to ‘Analipseos’ Station, the single system was considered as the optimum one; the results of the trial field are included in the data analysis and evaluation presented in the thesis (chapters 6 and 7).

![Figure 63: Execution of trial field in ‘Patrikiou’ Station](image)

Thomas Kimpritis, Imperial College London – MPhil Thesis, September 2013
6. Data analysis from the two Thessaloniki Metro station projects

6.1 Jet Grouting Diameter - Correlation with executional parameters and soil characteristics

One of the main issues of the Jet Grouting technique that is primarily analysed in the current thesis is the diameter of the constructed element. It will be investigated which are the main factors that influence the diameter, which issues are in accordance with the literature and under which circumstances it can be optimized during the execution of a project. For the analysis, it will be utilised the data gathered by the case studies mentioned in chapter 5 and the results will assist in the development of a practical model for the calculation of the diameter. In principle, the data collected by the Thessaloniki Metro will be used and the whole analysis and the developed model can be further used either directly for projects which present soil conditions (mixture of sand, gravel, silt and clay and alterations) similar to those that ‘Analipseos’ and ‘Patrikiou’ Stations have, or as an example for other projects, since it is clearly explained the data that are required.

In this section (6.1), wherever the unconfined compression strength is mentioned (in correlation with the diameter or other units), it is referred to the mean value of the wet samples that were tested after 28 days for each column. For instance, in Diagram 5, for each value of the diameter of a Jet Grouting element, the respective one of the UCS is the mean value of all the wet samples that were obtained at that particular column and were tested in 28 days. It is also mentioned that except for the lifting speed of the Monitor which varies, all the other executional parameters of the Jet Grouting method remain constant and are tabulated in Table 10.

<table>
<thead>
<tr>
<th>Jet Grouting main components</th>
<th>Jet Grouting Parameters</th>
<th>Units</th>
<th>Single</th>
<th>Triple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grout</td>
<td>Pressure</td>
<td>bar</td>
<td>400</td>
<td>80</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>Nozzles Diameter</td>
<td>mm</td>
<td>4,5</td>
<td>9,0</td>
</tr>
<tr>
<td>Water</td>
<td>Pressure</td>
<td>bar</td>
<td>-</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>lit/min</td>
<td>-</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>No of Nozzles</td>
<td></td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Nozzles Diameter</td>
<td>mm</td>
<td>-</td>
<td>4,5</td>
</tr>
</tbody>
</table>

Table 10: Jet Grouting Parameters that were used during the case studies
As far as the Thessaloniki Metro sites are concerned, the results of the whole investigation are depicted in the following diagrams and analysed based on the type of soil. The data that were required considering the ground properties were the unconfined compression strength as well as the SPT blows at certain depths of interest. For the columns that were examined in the current thesis, the soil data (UCS and SPT) are derived from the site investigation boreholes closest to the test columns. Every Jet Groutiing element corresponds to the closest borehole in the Station area. For example, in Diagram 7, in a specific test column (where its diameter was verified at a certain depth (for instance in 22,5m depth) as 1,28m, it is then checked which is the closest borehole and what is the SPT value at 22,5m depth (in this example 46 blows). The same procedure is repeated for the whole investigation and diagrams that are presented in Chapter 6.

It is noted that the diameter, which is mentioned in the diagrams of the following pages, was verified by the method of inclined core drilling; hence its accuracy is considered as high.

The evaluation of the data given in Diagrams 4 to 8 results in number of conclusions.

First, it can be seen that in most cases where the ground was mainly sandy/gravel the diameter achieved was relative bigger than in cases where soil mass was silty/clayey.

- In mainly sandy/gravel type of soil (in total 33 columns were tested): the mean value of the diameter was 1.5 m whereas the minimum value was 1.2 m and the maximum 2.0 m.
- In mainly clayey/silty type of soil (in total 28 columns were tested): the mean value of the diameter was 1.4 m whereas the minimum value was 1.1 m and the maximum 1.8 m.

Diagram 4 illustrates the above described situation. In addition, it is noted that as expected, an increase in the lifting speed of the monitor reduces the achieved diameter. The inclination of the trend line of Diagram 4 shows that the influence of the lifting speed was not so crucial for the diameter achieved. Contrary to lifting speed, Diagram 5 shows that the diameter of an element is not influenced by the mean value of the unconfined compression strength from tested wet samples taken from corresponding Jet Grouting columns.

An interesting observation is the role of the specific weight of the fresh Jet Grouting material (obtained through the wet sampling process) on the diameter. No reference to this aspect has been found in the Jet Grouting literature. In cases where the sand and gravel are the main part of the soil mass the mean value of the specific weight of Jet Grouting (wet sampling) is 1.62 t/m³ with a the minimum value of 1.46 t/m³ and a maximum value of 1.75 t/m³. On the other hand, in cases where the soil type is primarily clayey or silty, the mean value of Jet Grouting (wet sampling) is the same as in sandy and gravel case, thus 1.62 t/m³, but with a minimum value of 1.37 t/m³ and a maximum value of 1.88 t/m³. Diagram 6 shows that in the sand and gravel environment, the diameter is generally reduced when the specific weight is increased whereas in clayey and silty areas, the diameter is not really influenced by the variation of the specific weight. This issue requires further elaboration and is discussed in the model presented in the following chapter.
The role of SPT values and the degree that influences the diameter of the Jet Grouting element is shown in Diagram 7. The diameter becomes smaller as the SPT values increase (in all types of soil – see Diagram 7). However, when considering the influence of the soil unconfined compression strength $q_u$ on the diameter, it can be seen in Diagram 8 that in sandy and gravel soil environment (where in this type of soil it was noticed the presence of a significant quantity of fine soil material as well), the diameter is not influenced at all by the variation of $q_u$ whereas in silt and clay the higher the $q_u$ value the smaller the diameter (Diagram 8). The result shown in the silty/clayey soils is considered to be sensible. The ranges of the SPT and $q_u$ values were in the sandy environment 6 to 50 for SPT and 45 to 171 kPa for the $q_u$ and in silty environment, 7 to 50 for the SPT and 59 to 236 kPa for $q_u$.

The analysis of the produced diagrams, created by data and measurements during the production of the Jet Grouting elements provides a basic idea of the way that the diameter is influenced by various factors involved with the Jet Grouting technique. Further analysis with quantitative tools might give a clearer and more accurate picture for the diameter issue and the way that it can be calculated. This is discussed in the next section. Due to the large variation in the results relating to the Jet Grouting processes (clear from Diagrams 4, 5, 6, 7 and 8), final relationships are given in terms of the trend lines shown.

Diagram 4: Diameter versus lifting speed in different soil conditions in Thessaloniki Metro

[Diagram 4: Diameter versus lifting speed in different soil conditions in Thessaloniki Metro]
Diagram 5: Diameter - UCS ($f_{\text{mean}}$) in different soil conditions in Thessaloniki Metro

Diagram 6: Diameter - $\gamma$ (of wet sampling) in different soil conditions in Thessaloniki Metro
Diagram 7: Diameter – SPT values in different soil conditions in Thessaloniki Metro

Diagram 8: Diameter – $q_u$ values in different soil conditions in Thessaloniki Metro
6.2 Diameter Calculation – Model Development

Following from the data analysis and the observations covered in section 6.1 further examination of the results is undertaken here taking account of the Jet Grouting technique and its influence on the achieved diameter. As has been mentioned in previous chapters, one of the main issues that influence the design of a Jet Grouting project and its quality control is how the design diameter is related to the final product obtained after the whole soil eroding process has been accomplished. Considering that the Jet Grouting process is a dependent on many factors which need to be mapped out and related to each other, a mapping can be carried out and its stakeholders can be investigated (Figure 64). In fact, what has to be pinpointed are the factors (see Figure 64) that influence the Jet Grouting process and hence; the diameter achieved and the strength as well.

![Figure 64: Jet Grouting mapping out - Factors that influence Jet Grouting process](image)

Evaluating the diagrams from section 6.1 together with the Jet Grouting mapping chart, a regression analysis for the estimation of the diameter of a Jet Grouting element can be attempted. The diameter is considered as the dependent variable which is mainly influenced by the soil conditions and the lifting speed of the Jet Grouting monitor and the drilling rods, when other parameters such as the pressure and the grout flow rate remain constant. Four independent variables are considered for the execution of the regression analysis; the lifting speed $z$ (cm/min), the specific weight of Jet Grouting fresh material which is in reality the specific weight of wet sampling $\gamma_{JG}$ (t/m$^3$), the unconfined compression strength of the soil $q_u$ (kPa) and the SPT N-value (blows). Hence, each diameter value corresponds to a specific value of the above four independent values. The soil data are reported in the Appendix of the current thesis.

The basic mathematical equation that the regression analysis is based on is:
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

\[
D = \alpha_1 \times z + \alpha_2 \times \gamma_{JG} + \alpha_3 \times q_u + \alpha_4 \times \text{SPT}
\]

where \(\alpha_1, \alpha_2, \alpha_3, \alpha_4\) are regression variables.

To improve the accuracy of the model, it has been produced in four clusters based on ranges of values of the lifting speed. The result of the regression analysis is presented below in 4 formulas. For each cluster (group), each independent variable is multiplied by a factor.

- **Cluster 1**: \(10 \leq z < 15\):
  \[
  D = -0.040 \times z + 0.861 \times \gamma_{JG} + 0.010 \times \text{SPT}
  \]

- **Cluster 2**: \(15 \leq z \leq 20\):
  \[
  D = 0.044 \times z + 0.615 \times \gamma_{JG} - 0.002 \times q_u + 0.001 \times \text{SPT}
  \]

- **Cluster 3**: \(20 < z < 30\):
  \[
  D = 0.046 \times z + 0.844 \times \gamma_{JG} - 0.003 \times q_u - 0.013 \times \text{SPT}
  \]

- **Cluster 4**: \(z \geq 30\):
  \[
  D = -0.012 \times z + 0.938 \times \gamma_{JG} + 0.002 \times q_u + 0.003 \times \text{SPT}
  \]

Where

- **D (m)**: diameter of Jet Grouting element;
- **z (cm/min)**: lifting speed;
- **\(\gamma_{JG}\) (t/m\(^3\))**: specific weight of Jet Grouting fresh element;
- **\(q_u\) (kPa)**: unconfined compression strength of soil samples;
- **SPT**: number of blows (SPT N-value).

The absolute error of the above formulas is 0.11m. This means that in every application of the above formulas, there could be an accuracy error in the range of 0.11m. For instance, if the diameter is calculated to be 1.65m, then, its actual value is between 1.54m and 1.76m. This error value is considered as more than acceptable for the requirements and the needs of Jet Grouting process. In addition, the above empirical equations are based on mathematics and there is not in all cases a physical explanation for the diameter result. However, checking the formulas in detail, various implications are derived and are noted below.

- It can be seen that the optimum lifting speeds \(z\) (cm/minute) for the execution of the project are \(15 \leq z < 30\) (clusters 2 and 3), as this results in the \(\alpha_1\) factor being positive.
- Further increase of more than 30cm/minute of the Monitor’s lifting speed acts negatively for the size of the diameter (cluster 4). This implication is a logical result in the concept of Jet Grouting method. On the other hand, a reduction of the lifting speed normally leads to larger diameters. However, in the current case studies, cluster 1 appears to result in a negative influence of too low lifting speeds (lower than 15cm/minute). Hence, it has to be stated that it is not a rule that a reduction in the lifting speed, which is also not economic for the project, always triggers a significantly positive result in the diameter issue. The author met similar cases in other Jet Grouting projects and countries; for example, in Norway, there was a case where after the execution of a trial field, the optimum lifting speed was set to be
20cm/minutes. The diameter was verified through the excavation method to 2.4m. During the trial field, a reduction of the lifting speed to a value of 10cm/minute led to a smaller column of approximately 2.0m.

- Regarding the specific weight of wet sampling (fresh Jet Grouting material), it is shown that, for all clusters, the higher its value, the higher becomes the diameter.
- In the first cluster, there is no factor for the $q_u$ value since it was much too low (lower than $10^{-3}$); thus it is omitted. This means that in this specific group, the unconfined compression strength of the native soil does not influence the size of the diameter of the Jet Grouting elements.

Last but not least, it is stated that using the above formulas, the process of calculating the diameter of a Jet Grouting element during the construction phase of a project, which is performed under similar soil conditions with comparable soil characteristics to those of the Thessaloniki Metro, becomes an easy and simple task without costs. In other case, if the Site Manager undertakes an extended investigation of the soil characteristics, then similar formulas can be produced for the quality control of any type of Jet Grouting project, since the executonal parameters are defined and the specific weight of Jet Grouting body in fresh condition can be measured on site. The current method is a practical way to estimate the diameter of Jet Grouting elements and is recommended for major projects where normally a trial field is carried out prior to the main works.
6.3 Jet Grouting Strength (Wet Sampling) - Correlation with Jet Grouting executional parameters and soil characteristics

The other major issue of the Jet Grouting technique that is analysed in this thesis is the strength of the constructed element. In this section, the way the strength (estimated by testing wet samples) is influenced by various factors involving the soil and Jet Grouting characteristics is investigated. For the analysis, the data gathered from the projects described in Chapter 5 collected during the Thessaloniki Metro construction are utilised. A database has been created of the factors that influence the strength of the final product. The intention is to be further used as a reference in future projects with similar soil conditions to those encountered on the Thessaloniki Metro. Generally in industry the strength of Jet Grouting columns is checked and controlled through core samples or even spoil samples. Little data have been published till now relating to strength based on the wet sampling process (receiving fresh Jet Grouting material just after the construction of the column). As it is a simple and cheap process, Diagrams 9, 10, 11 and 12 presented below are of great interest to the research environment of Jet Grouting.

In this section (6.3), wherever the unconfined compression strength is mentioned (in correlation with various units), it relates to the mean value of the wet samples that were tested after 28 days for each column. For instance, in Diagram 9, each value of strength shown relates to the mean value of all the wet samples that were obtained from one particular column which was constructed with the respective water/cement ratio and those samples were tested after 28 days. It should also be mentioned that the all the diagrams were produced having fixed values for the following executional parameters (see Table 10 on page 88 – chapter 6.1). Similarly to the diameter case, the lifting speed of the monitor varied during the application of the technique. It should be stated that the influence of lifting speed to the Jet Grouting strength has been checked and no influence or correlation found between them.

Regarding the Thessaloniki Metro sites, the results from the investigations are presented in diagrams and analysed based on the type of soil. The data that were required considering the ground properties were the unconfined compression strength as well as the SPT blows at certain depths of interest. For the columns that were examined in the current thesis, the soil data (UCS and SPT) are derived from the site investigation boreholes closest to the test columns. Every Jet Grouting element corresponds to the closest borehole in the Station area. For example, in Diagram 11, in a specific test column (where its mean values of the wet samples was verified at a certain depth (for instance at 22.5m depth) as 8.0MPa for a w/c=0.9, it is then checked which is the closest borehole and what is the SPT value at 22.5m depth (in this example 46 blows). The same procedure is repeated for the whole investigation and diagrams that are presented in Chapter 6. It is also stated that for the needs of the current research and the produced diagrams, the wet sampling process was carried out at certain depths of interest.

Finally, in similar manner to the diameter analysis presented before, due to the large variation in the results relating to the Jet Grouting processes (clear from the Diagrams 9, 10, 11 and 12), the final relationships are given in terms of the trend lines shown.
Evaluation of Diagrams 9-12 allows a number of points to be discussed and conclusions drawn:

First, the results involve both the single and triple systems. Regarding the soil classification, in most cases where the ground was mainly sandy/gravel the Jet Grouting strength was relative higher than in cases where silty/clayey soil was the main ground ingredient. For high water/cement ratios (1.2 to 1.3), the strength seems to be at the same level for both types of ground conditions (Diagram 9). The following can be specifically noted.

- In the mainly sandy/gravel type of soil (in total 32 columns were examined including approximately 2 to 3 samples per column for tests): the mean value of the Jet Grouting strength (for all water/cement ratios) was 5.7 MPa, whereas the ranges were from 1.4 MPa (coming from a column with a water/cement ratio equal to 1.0) up to 10.4 MPa which relates to a column with a water/cement = 0.9.
- In the mainly clayey/silty type of soil (in total 28 columns were examined including approximately 2 to 3 samples per column for tests): the mean value of the strength (for all water/cement ratios) was 4.3 MPa, whereas the ranges were from 1.3 MPa (coming from a column with a water/cement ratio equal to 0.6) up to 8.8 MPa which relates is a column with a water/cement = 0.9.

Diagram 9 illustrates the above observations. Additionally as expected, the increase in the water/cement ratio reduces the achieved strength since less cement quantity is injected in to the soil.

As was checked for the diameter case, the role of the specific weight of the fresh Jet Grouting material (obtained through the wet sampling process) on the strength was investigated as well. The ranges and variation in its values are: in sand and gravel the mean value is 1.62 t/m$^3$ (referring to the wet sampling procedure), whereas the minimum value is 1.46 t/m$^3$ and the maximum value 1.75 t/m$^3$. In clay or silt, its mean value is the same as in sandy and gravel case, thus 1.62 t/m$^3$, and its minimum value equal to 1.37 t/m$^3$ the maximum equal to 1.88 t/m$^3$. Diagram 10 illustrates a clear picture about its influence on the strength. For any soil conditions, the strength increases as the specific weight increases and this influence is more intense in soil where the sand and gravel are the primary main ground components. The above implies that regular measurements of the specific weight of wet sampling (together with some unconfined compression tests) assist the Geotechnical Engineer to gain quickly an impression concerning the strength and to react, if need be, by setting a lower water/cement ratio. Low values of the specific weight (thin Jet Grouting material) lead to low strength values.

Apart from the above, the strength of Jet Grouting body is also influenced by the soil characteristics. Regarding SPT N-value, in any type of soil, the higher the N-values, the higher becomes the achieved strength (Diagram 11). On the other hand, considering the $q_u$ values, in the mixed soil of silty sand with gravel, the strength gets lower as $q_u$ increases. This probably occurs due to the fact that a large quantity of fine material in a sandy and gravelly environment, on one hand gives to the soil high strength (high $q_u$ value), but on the other hand, the presence of this fine material (even after the Jet Grouting process) reduces the strength of Jet Grouting body. In cases where there are mixed soil conditions, and the
clayey and silty material represent a greater percentage than the sand, the strength of Jet Grouting material was not influenced (Diagram 12).

Finally, as was mentioned in the diameter analysis, the ranges of the SPT and $q_u$ values were in sandy environment from 6 to 50 for the SPT and from 45 to 171 kPa for the $q_u$ and in silty environment, from 7 to 50 for the SPT and from 59 to 236 kPa for the $q_u$.

**Diagram 9:** UCS mean values of wet sampling – w/c ratio in different soil conditions
‘The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.’

Diagram 10: UCS mean values – γ specific weight (both for wet sampling) in different soil conditions

Diagram 11: UCS mean values of wet sampling – SPT blows of native soil
6.4 Jet Grouting Strength – Core and wet samples comparisons

6.4.1 Introduction
Continuing to the analysis that took place in section 6.1.3, the author elaborates in more detail on the strength issue and analyses the data gathered from the construction project case studies from the Thessaloniki Metro, concentrating on the way that the strength can be evaluated. More specifically, the mean value \( f_{\text{mean}} \) and the characteristic value \( f_{\text{m,k}} \) based on the criteria of the new DIN 4093 are calculated based first on the wet sampling process and secondly based on the coring process. Comparisons between the respective values are made and the data are checked separately for the two Stations (‘Analipseos’ and ‘Patrikiou’). The goal of this procedure is the investigation of the variation of the strength values \( f_{\text{mean}} \) and \( f_{\text{m,k}} \) for both core drilling and wet sampling process for various water/cement ratios and in a further stage the development of a correlation between the core samples and the wet ones.

It is noted that more than five hundred samples in total were tested for the whole analysis and the wet and core samples were both tested after 28 days.
6.4.2 Strength Results based on wet sampling

The author presents the results gathered during the extensive quality control programme that was applied in ‘Analipseos’ and ‘Patrikiou’ Stations in Thessaloniki Metro construction. It is stated that $f_{m,k}$ (characteristic value) and $f_{\text{mean}}$ (mean value) were calculated based on new DIN 4093.

Diagrams 13 and 14 present the results of the calculations of the mean values and the characteristic values of the wet sampling process for ‘Analipseos’ and ‘Patrikiou’ Stations; the single Jet Grouting system was utilised and data were obtained for various water/cement ratios (from 0.8 up to 1.3). An impression can be gained concerning the severity of the new DIN criteria considering the calculation of the characteristic strength value.

Diagram 13: Wet Sampling – Strength results versus w/c (‘Analipseos’ Station)
6.4.3 Strength Results based on core samples

In this section, the results gathered from the extensive quality control programme that it was applied in ‘Analipseos’ and ‘Patrikiou’ Stations in Thessaloniki Metro construction are presented. Again the that \( f_{m,k} \) (characteristic value) and \( f_{\text{mean}} \) (mean value) were calculated based on new DIN 4093.

Diagrams 15 and 16 present the results of the calculations of the mean values and the characteristic values of the core samples for ‘Analipseos’ and ‘Patrikiou’ Stations; the single Jet Grouting system was utilised and data were obtained for various water/cement ratios (from 0.8 up to 1.3). Similar to the wet sampling process, Diagrams 15 and 16 depict again the severity of the new DIN criteria considering the calculation of the characteristic strength value.
Diagram 15: Coring – Strength versus w/c results (‘Analipseos’ Station)
6.4.4 Comparison between wet and core samples

Analysing the above diagrams (13, 14, 15 and 16), a comparison can be made between the results from core samples and wet samples as shown in Diagrams 17, 18, 19 and 20. In relation to those diagrams, the following points can be mentioned:

- ✓ The core samples always give higher values than the wet ones, especially the mean value.
- ✓ In ‘Patrikiou’ Station, considering the single Jet Grouting system, the mean and characteristic values of wet samples and cores are lower than the respective ones in ‘Analipseos’ Station for the same water/cement ratios. Taking into consideration that the soil in ‘Patrikiou’ Station is slightly weaker (section 5.2.4) than at the ‘Analipseos’ Station, the outcome seems logical and at the same time shows, that the strength of the soil influences the strength of the Jet Grouting body as well.
- ✓ In ‘Patrikiou’ Station, with the application of the triple system, a large difference between the results of wet sampling and coring in terms of the mean and characteristic strength value was noted whereas at the ‘Analipseos’ Station this did not happen.
- ✓ Despite the difference in the ranges in ‘Analipseos’ and ‘Patrikiou’ Stations, and investigating the case for the same water/cement ratios, the analogy of the mean values $f_{m\text{ coring}}/f_{m\text{ wet sampling}}$ was very similar and approximately equal to 1.2.

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Diagram 16: Coring – Strength versus w/c results (‘Patrikiou’ Station)
Diagram 17: Comparison ($f_{\text{mean}}$) between coring and wet sampling (Analipeos Station)

Diagram 18: Comparison of characteristic values ($f_{m,k}$) between coring and wet sampling (based on new DIN 4093) (Analipeos Station)
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

Diagram 19: Comparison ($f_{\text{mean}}$) between coring and wet sampling (Patrikiou Station)

Diagram 20: Comparison of characteristic values ($f_{m,k}$) between coring and wet sampling (based on new DIN 4093) (Patrikiou Station)
6.4.5 Correlation between Strength and Elasticity Modulus

Another topic in the fields of strength which is of great interest is the value of the modulus of elasticity of the Jet Grouting material. The modulus of elasticity is the mathematical description of an object or substance’s tendency to be deformed elastically (i.e., non-permanently) when a force is applied to it. The elastic modulus of an object is defined as the slope of its stress–strain curve in the elastic deformation region.

The author gathered information from laboratory unconfined compression strength tests (on core samples of Jet Grouting material) where the secant modulus was calculated. The results are presented in Diagram 21 in correlation with the respective unconfined compression strength values.

![Diagram 21: Correlation between strength (mean values of core samples) with secant modulus of elasticity](image)

The goal of Diagram 21 was to examine the correlation between the UCS strength value of the core samples and the Secant modulus of elasticity. It can be clearly seen that in general, an increase in strength value results in a higher value in the elasticity modulus. A statistical analysis was carried out (Diagram 22) in order to define the factor that correlates the unconfined compression strength with the secant modules of elasticity that corresponds to the 50% of the maximum strength $E_{s,50}$. The factor is defined as the ratio $E_{s,50}/$UCS strength and its mean value was 625 whereas the 81% of the total values of the factor were between 250 and 750.
Diagram 22: Statistical analysis of the results derived by secant modulus of elasticity with cores
7. Data analysis and evaluation

7.1 Introduction

In this chapter, the evaluation that has been carried out to now is presented, considering the various diameter control methods. The author draws on data from his own experience gained from applications in Europe and also from the experience of other colleagues. Wherever a method was not applied by the author himself, the evaluation of this particular technique takes place according to the available publications and the current literature.

7.2 Evaluation of Diameter Control Methods

EXCAVATION and CORING METHOD

These methods are considered to be the most reliable. The coring method potentially has some risks, for example where due to differences in soil conditions, an inclined core drilling could lead to either an under- or over-estimation diameter. Figures 17 and 18 (page 35) present such a case which can occur due to either different soil strata (as is the case in the aforementioned charts), or to a local soil abnormality, sudden hard ground for instance, which can lead to a conservative design value of the diameter. This risk can be mitigated by the execution of a second inclined drilling in order to check any totally unexpected diameter values. In general, the inclined coring still remains the most reliable method after excavation of the Jet Grouting column.

THERMIC METHOD

The current method was widely applied by the author and its accuracy was checked either with the excavation method or with the inclined core drilling method. The results indicate that it is a promising method. By evaluating the gathered data Diagrams 23, 24 and 25 have been produced in which \( D_{\text{coring}} \) is the diameter value that derived from the length of the core taking into consideration deviations of the coring itself and the Jet Grouting element and \( D_{\text{thermic}} \) is the value calculated by the thermic method).
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

Diagram 23: Statistical analysis of the results derived by diameter measurements with core drilling and thermic method.

From the analysis executed in Thessaloniki Metro and analysing 73 pairs of diameter values estimated by the inclined coring method and thermic one, the following ranges were observed (Diagram 23):

- 41% of the ratio $D_{coring}/D_{thermic}$ is between 0.85 and 1.15,
- 27% of the ratio $D_{coring}/D_{thermic}$ is between 0.55 – 0.85. ($D_{thermic}$ over-estimated resulting in unconservative diameter value) and,
- 27% of the ratio $D_{coring}/D_{thermic}$ is between 1.15 – 1.30. ($D_{thermic}$ under-estimated resulting in a conservative (safe) diameter value).

In the analysis that was done, the comparison between the thermic and coring values was done at the same approximately position along the Jet Grouting element in order to try to avoid any irregularities in diameter with depth. In addition, any values where the diameter was much lower than 1.0m (this implies the presence of rocks or extremely hard soil), were excluded from the analysis.

Further analysis focusing on the soil conditions indicates that the distribution shown is influenced by the ground over the depth at which the various tests were performed. Assuming that the core drilling method is the most accurate way in estimating diameter, it seems that the thermic model provides diameter values that in general are:
- Larger than the real ones in clayey/silty soils;
- smaller than the real ones in sandy/gravel soils.

Diagram 24 has been produced for clayey/silty type of soils:

**Diagram 24: Thessaloniki Metro measurements, average value of \( \frac{D_{\text{coring}}}{D_{\text{thermic}}} = 0.88 \), standard deviation 0.20.**

From the analysis of the results from the Thessaloniki Metro, the following has been established for clayey/silty soils (33 cases - Diagram 24):

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

Therefore from the above diagram and the average value, it can be seen that the thermic model gives results which are 12% more optimistic than the actual diameter of the column.

Diagram 25 has been produced for sandy/gravel types of soil.
From the analysis of the results from the Thessaloniki Metro, the following has been established for sandy/gravely soils (43 cases - Diagram 25):

- 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.

Therefore from the above diagram and the average value, it can be seen that the thermic model gives results which are 12% more conservative than the actual diameter of the column. Thus, the results are on the safe side and the diameter is under-estimated.

The under-estimation of diameter in sandy and gravelly soils together with the over-estimation in clay and silt were also confirmed in London during the Jet Grouting works that took place at Victoria Station. Further investigation is required regarding the accuracy of the model in cohesive soil. The main analysis has to focus in clay and silt since it seems that the results are not on the safe side.

According to author’s experience, it has been observed that when using the triple system, the in-situ curves fit much better with the theoretical ones than the double or single system. This may be because of the way that the thermal conductivity of the soil is simulated in the
thermic model. In triple system, due to the use of water in the eroding phase and the filling with grout, the Jet Grouting element has a more homogenous body with less soil inclusions inside.

It can be concluded that the thermic method presents promising results and has a very sound scientific background which is constantly being improved. It is recommended for further use by Jet Grouting Site Managers and Researchers.

As a final point, it should be noted that the Engineer who uses the method needs to have the ability and the experience to assess the data coming from the thermic model. The type of soil, the soil temperature, the Jet Grouting process and other factors can influence the calculation and the Engineer has to evaluate all the issues before assessing the temperature measurements. It seems that the system needs a certain ‘calibration’ for the specific soil to which it is applied. Sometimes, even the country where the model is used and its special conditions regarding the soil and grout temperature can influence the results. For instance, in Greece, the Jet Grouting mixture starts at a temperature of 35 to 60 degrees while the soil temperature is 16°C to 18°C, whereas in Norway, the Jet Grouting mass has an initial temperature of 15°C to 25°C which the soil temperature is 6 degrees. Such issues influence the diameter calculation due to the way that the reaction of cement with water is getting further under different soil and environmental temperature conditions. For instance, in Austria, if a Jet Grouting element with a diameter of approximately 2.0m requires 50 hours to reach the maximum temperature inside the column, in Norway, a period of approximately 80 hours will be needed.

In reality, it is suggested, that before the application of the model, a trial field is made in order to check the correlation of the results of the thermic measurements with those from core drillings or exposed columns. The model could then be used extensile on site with a greater degree of confidence or accuracy.

MEASUREMENT OF THE SPECIFIC WEIGHT OF THE SPOIL MATERIAL
This method has also been widely applied by the author; in some cases the results related well to the actual diameter. An accurate measurement of the specific weight of the spoil material is required along with precise soil data concerning the grain size distribution. The definition of the exact value of the ground replacement factor (A₈) still remains a topic that has to be verified since the ranges of its values vary. Finally, it should be noted that the assumption, that the water/cement ratio within the Jet Grouting column and the spoil material is the same, is not considered to be valid.

If the method can be verified during a field trial, then, it can be readily applied as part of a quality control programme which provides regular measurements of the diameter of Jet Grouting elements.

Finally, Diagram 26 shows that, when the A₈ (soil replacement factor), remains stable, the higher the specific weight of the spoil material, the higher the value of the estimated diameter. However, this was not confirmed by the author during his site measurements.
Diagram 26: Diameter vs $A_B$ factor for 4 values of spoil density $\rho_r \, [gr/cm^3]$ (Lesnik, 2003)

**CYLJET**

Regarding this method, although the author has no personal experience, the literature suggests that the Cyljet model gives measurements that are approximately 10% less in (Pierre, 2002). The issue of installing a plastic pipe just after the column construction can be problematic in specific soil conditions and in general with depths more than 10 metres. Additionally, if the jetting length is long, it will again be difficult to install the plastic tube. Finally, the inventor suggests that in the case where the plastic pipe cannot be installed within the fresh column then a hole for installation has to be drilled as soon as possible; the exact working sequence is not clear. The method seems to be often utilised in France.

**WAVE ANALYSIS**

Information from the site in Columbus, USA, where the wave analysis technique was applied, suggests that the geophone data correlates very well with the column diameter and the overlapping between the two constructed columns. Some of the trial columns were excavated and exposed to a depth of 4.5m and confirmed the wave analysis measurements.

**TURBULENT KINEMATIC THEORY**

This approach seems to have a background based on empirical formulae. It takes into consideration the soil characteristics but the lifting speed during the jetting process is not mentioned. In the literature, this is considered to be a crucial factor concerning the size of the achieved diameter. In addition, the factor $b$ is very generally defined with a large range for the same type of soil.
The fact that the lifting speed of the monitor is not included in the formulae used in the model implies that there is still much scope for improvement. Finally, it should be noted that in most cases such empirical models require a certain ‘calibration’ when they are applied in other situations and countries concerning the estimation of various empirical coefficients; for instance the factor \( b \) may have a different value in Europe to the one that has been applied in the USA.

**EVALUATION OF DIAMETER – ANALYTICAL APPROACH**

The analytical approach Carnevale, et al. (2011) which was described in section 3.2.3 presents both advantages and disadvantages.

**Advantages:** It takes into consideration both the soil characteristics (e.g. unconfined compression strength \( q_u \), permeability \( k \), Poisson’s ratio) and Jet Grouting parameters (e.g. grout or water pressure, lifting speed, rotations/minute, nozzle diameter).

**Disadvantages:** It was not found any references (apart from Carnevale et. al. (2011)) in the literature or Projects where this method was applied in order to be checked the accuracy of the method.

The background theory of the mentioned formulae presented or the Excel spreadsheets have not been checked in detail by the author.

The good comparisons cited in the case studies by Carnevale et al (2011) between the measured and the calculated values of the Jet Grouting diameter suggest that there is promise in the further use of theoretical models. As with more methods, more case studies would assist in the improvement of such calculation models along with their prediction accuracy.
7.3 Summary – Conclusions for the Diameter issue

The calculation or, perhaps more appropriately, the estimation of the diameter of a Jet Grouting element is one of the most crucial issues of the technique and remains one of the most important aspects in the quality control of a geotechnical project. In the previous chapters, the methods available in industry were described and the advantages and disadvantages were analysed and discussed. Further methods will be invented in the coming years and the current ones will be improved in terms of their accuracy.

Even though the shape of a Jet Grouting column is approximately cylindrical, the author strongly believes that the diameter estimation remains a difficult and ambiguous task. Considerably engineering judgment along with an extensive assessment of the data available at the construction site are required no matter which method is implemented for the estimation of the diameter. Adopting a practical perspective, the author suggests that considering geotechnical issues associated with the Jet Grouting technique, the steps described below have to be followed:

1. Define the function of the Jet Grouting elements: e.g. a totally different design approach is regarded depending on whether the project involves the construction of a retaining wall or a sealing wall. In the case of a Jet Grouting slab construction, it must be determined at the outset if the slab works as a sealing element or a strutting one. The latter is a deformation and strength problem (hence the quantity of cement is crucial), whereas in a sealing project, the intersection of the Jet Grouting elements is more important (thus, the achieved diameter) rather than the final strength that the body will acquire.

2. Focusing on the diameter issue and based on the intended use of the Jet Grouting elements (Step 1), what exactly is meant by the Jet Grouting diameter has to be defined. In all cases, the achievement of an average (or design) diameter is usually the goal set in order to meet the project requirements. Figures 65 and 66 elaborate on the above consideration regarding the design requirements of the Jet Grouting elements. Three scenarios with different soil conditions are depicted, where the average (or design) diameter could be viewed as the same but also different depending on the Jet Grouting application.
In Figures 65 and 66, the following conditions are represented:

Column ‘A’ is the result of applying the Jet Grouting process in an absolutely homogenous soil.

Column ‘B’ is a Jet Grouting element which was produced in a totally inhomogeneous soil where at certain depths there are hard ground layers.

Column ‘C’ is a typical Jet Grouting element installed in a homogenous soil whose strata (soft or hard) are clearly defined.

If the Jet Grouting body works as a strutting slab, then in all above cases A, B, C, the average diameter is the same. However, even if the diameter achieved is locally less...
than the defined average one, then the soil is so hard that cannot be eroded and in addition, it means that the soil acquires such strength that is able to transfer the strutting force. In such cases, the intersection among other neighbour columns is required.

Furthermore, if the function of the Jet Grouting block is to seal a certain area, the average diameter differs from case A to B or C, since a more conservative approach has to be adapted (see Figure 66).

Figure 66: 3 types of Jet Grouting elements, based on different soil conditions, with different average diameter depending on the function of Jet Grouting (design approach/example for a sealing slab)

3. Define and decide upon various factors concerning:
   - the application of the technique;
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

- the executional parameters (Jet Grouting system/pressure/flow rate/lifting speed/and the other units given in Table 3 - see page 25) through a trial field or based on past experience and data;
- the construction phase.

4. The final step concerns is concluded the quality control of the project and especially for diameter issue. This involves determining which of the available methods described in Chapter 3, will or can be applied. Having considered the many approaches available, the author still believes that the excavation and the inclined core drilling methods remain the most reliable ones. It is important to remember that a project optimization requires not only a certain level of quality, but also a balance with time and cost (Figure 67).

![Figure 67: Project Optimisation](image)

Apart from excavation and core drilling (which require much time and cost compared with other methods), all methods are promising but there is scope for improvement. The author suggests that whatever method is used, apart from excavation or core drilling, it first has to be tested and applied under the specific side conditions (using a trial field for instance, or based on past experience and data under similar soil conditions) and be verified first with one of the two aforementioned methods. Therefore, a certain ‘calibration’ will take place and in this way the accuracy of the model should be optimised.

What can be also applied and is strongly recommended, especially in major projects where a trial field takes place prior to the main works, is a detailed analysis of the available data and the development of a model similar to that presented in section 6.2. It provides an accurate and practical way of constant control of the diameter of Jet Grouting elements at minimum cost during an extended production sequence. It involves the main components of the Jet Grouting process (soil and Jet Grouting parameters): the main challenge for its application...
concerns persuading and encouraging the Site Managers to collect the data, both from the geotechnical report and the site production (e.g. specific weight of wet sampling).

7.4 Strength Evaluation-Conclusions

Comparing the various curves derived from cores and wet samples for the two stations in the Thessaloniki Metro project (presented in section 6.4), the following points can be made considering cement quality CEM II 32.5N.

1. For w/c ratios = 0.5 to 0.6 (Triple System), the ratio of the UCS values for the mean values \( f_{\text{mean (coring)}} / f_{\text{mean (wet sampling)}} \) is approximately 3.1. There is a significant difference between the wet sampling results and cores when using the triple system. This probably occurs due to the amount of water that is injected into the soil during the soil erosion process.
2. For w/c ratio = 0.8, the ratio of the UCS values for the mean values, \( f_{\text{mean (coring)}} / f_{\text{mean (wet sampling)}} \) is approximately 1.1 (Single Jet Grouting System).
3. For w/c ratios = 0.9 to 1.0, the ratio of the UCS values for the mean values, \( f_{\text{mean (coring)}} / f_{\text{mean (wet sampling)}} \) is approximately 1.2 (Single Jet Grouting System).
4. For w/c ratios = 1.1 to 1.3, the ratio of the UCS values for the mean values \( f_{\text{mean (coring)}} / f_{\text{mean (wet sampling)}} \) is approximately 1.9 (Single Jet Grouting System).
5. For w/c ratios = 1.1 to 1.3, it is obvious that whenever the w/c ratio value is higher, the wet samples strength values become weaker compared with those from the cores; this means that when the cement quantity in a sample is low, the core sample gives much higher results than the wet sample.

The above results are summarised in Table 10 below.

<table>
<thead>
<tr>
<th>w/c</th>
<th>Jet Grouting System</th>
<th>( f_{\text{mean (coring)}} / f_{\text{mean (wet sampling 28days)}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Triple</td>
<td>3.1</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>Double or Single</td>
<td>1.1</td>
</tr>
<tr>
<td>0.9</td>
<td>Double or Single</td>
<td>1.2</td>
</tr>
<tr>
<td>1.0</td>
<td>Double or Single</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 11: Correlation \( f_{\text{mean (coring)}} / f_{\text{mean (wet sampling in 28 days)}} \) for various w/c ratios
In general, as has already been mentioned in section 6.4.4, the cores give higher UCS values than those from the wet samples. This can be explained by the fact that the cores that are tested are always the ‘best’ ones, whereas the same does not occur with the wet samples which are collected just after the construction of the columns and which are all tested. Additionally, the wet samples which preserved in the laboratory, while the cores have matured and hydrated in the best conditions (within the ground); thus they give higher values. Finally, it should be noted that the quality of the wet samples is influenced by their method of transportation to the laboratory during which they face the risk of the creation of cracks which were not originally present at the beginning.

The strength issue is a crucial topic in many Jet Grouting projects. It should be noted that the Jet Grouting product comprises a ground improvement geotechnical technique and should not be considered in the same way as concrete or grout. In most cases, the designer defines the requirements of the construction methods and the strength values that the final product should acquire. The Jet Grouting strength and its evaluation, for the needs of a project’s quality control, involve two main issues that have to be clarified before a project commences:

1. The method that should or has to be adopted has to be defined; (wet sampling or core samples);

2. how will the unconfined compression test results be evaluated? Many standards (Eurocodes, DIN, etc) imply that there are various ways of evaluating the results.

For case 1, it is noted that each method involves advantages and disadvantages. The cores require a maturing duration of 28 days and a drilling rig brought on to site at a later date for their collection involving both more time and cost while the method leads to higher UCS values and hence to less conservative and design. The wet samples can be taken easily, more economic (using a simple sampler that is attached to the drilling rods of the rig) just after the construction of a Jet Grouting element and a first impression or evaluation is possible after the 7 days UCS tests.

In case 2, the point is that in many cases, the standards are not always appropriate for line with the engineering case in hand and the Geotechnical Engineers must take this issue into consideration before the assessment of the strength results. For instance, according to DIN 4093 (2012), the characteristic strength value has to meet three criteria, one of which is to adopt the minimum UCS value of the tested samples: this could lead to really conservative UCS values and design approach.

In this thesis, further elaboration on the strength issue has included an analysis of UCS results from wet samples at 7 and 28 days compared with those from UCS results from core samples. A certain correlation has been developed between the strength values as is illustrated in Table 11 with the ‘Kit Factor A’. Thus, if an engineer acquires UCS strength data from wet samples tested after 7 days, the corresponding wet sampling mean UCS strength value after 28 days or the respective UCS from core samples can be readily calculated. For instance, if the mean UCS value from wet samples, tested after 7 days, from
a column, executed with a water/cement ratio of 0.9, is 3 MPa, then it is possible to estimate that the mean UCS value from wet samples after 28 days would be 1.7 x 3.0 = 5.1 MPa and the mean value relating to core samples would be estimated to an approximate value of 2 x 3.0 = 6.0 MPa.

Table 12: Correlation between wet sampling and coring mean UCS values—calculation of mean values through ‘KiT Factor A’.

In addition to the above conclusions and results, the author makes the following suggestion regarding the UCS strength issue.

Strength evaluation method.
Having examined all the available data from various case studies, the author proposes that the wet sampling method is the most objective and accurate method. Material from the fresh Jet Grouting column is taken just after its construction and is considered to be the most representative of the final product. There are some factors that could influence and reduce the wet sample strength (e.g. creation of cracks during transportation to the laboratory; water inside the sampler during the sampling process; proper preservation of samples in a moist environment). These might be considered as ‘extra safety’ for the final UCS adopted. If the wet sampling process is not possible due to the soil conditions, the other alternatives can be applied related to core samples and spoil material. If this is the case, the results are probably not so representative of the Jet Grouting body, because in the coring case, only the ‘best’ cores are tested and in the spoil samples case, the tested material is derived from the Jet Grouting element. However, generally, it is better to gain some UCS information for a project rather than having nothing. Regarding the evaluation of the strength of cores or spoil samples and in order to estimate the strength value of a Jet Grouting body, the Site or Project Manager has the option either to reduce the core...
samples strength (it is always higher than the one obtained from wet sampling) or in the spoil material case, to take into account that the column strength is in most cases higher than the spoil UCS.

- **Trial field execution.**
  The author recommends the execution of a trial field with columns that are constructed with various water/cement ratios. In this way, an overview of the strength can be obtained and the project can be not only technically but also financially optimized. The Jet Grouting material consists of water, soil and grout; in some situations excessively reducing the water/cement ratio (thus much more cement quantity per cubic metre of Jet Grouting body), does not have a significant increase in the final strength (for example in peat or soft clayey ground conditions).

- **Data collection and evaluation – Geotechnical design.**
  The way that the strength data are evaluated and the design or the characteristic value calculated, is another crucial topic. The author recommends using standards e.g. (DIN 4093, 2012), but in a first stage and based on the engineering experience of the Geotechnical Engineer assessing the data, both the very low and very high values of the created database could be excluded. In this respect there is no general rule, keeping as a basis the mean UCS value and some safety factors, the Designer in cooperation with the Jet Grouting specialist Contractor can decide on a design strength. Past data from similar soil conditions or neighbouring projects can also be taken into account. During the project execution, the strength has to be constantly checked and controlled and any deviations from the design value should lead to consistency measures being taken trigger reactions on site (e.g. further execution of the Jet Grouting works with a lower water/cement ratio). This is another reason why the wet sampling process is strongly recommended: after obtaining the 7-day UCS results and utilizing also the ‘KiT Factor A’, there is scope for contingency measures and the application of extra safety procedures during Jet Grouting construction works.

- **Proposed strength ranges for mixed soil conditions**
  According to the experience gained in Jet Grouting works in mixed soil conditions where the soil environment is characterized as clayey/silty/sandy with some gravel, the author suggests the following points regarding the wet sampling case.

  - In ground conditions where sand is the major material in the grain size distribution where sampling might be difficult, a mean value of approximately 6.0 MPa might be adopted for a water/cement ratio equal to 0.9 (UCS values range between 2.0 and 9.0 MPa for water/cement ratios 1.3 and 0.8 respectively); then a safety factor based on the standards (DIN 4093, 2012) can be applied for the calculation of the characteristic and design UCS values.
  
  - In ground conditions where silty/clayey material is the major one in the grain size distribution. A mean value of approximately 4.5 MPa might be adopted
for a water/cement ratio equal to 0.9 (UCS values range between 1.7 and 8.0 MPa for water/cement ratios 1.3 and 0.8 respectively); then a safety factor based on the Standards (DIN 4093, 2012) can be applied for the calculation of the characteristic and the design UCS values.

- Finally, considering the cement quantity that remains in the Jet Grouting element in mixed soil conditions, the author suggests that half of the injected quantity remains in the body. This is an assumption that is taken into account, is based on the author's experience and is used as a tool in the tender phase of a project.
8. Conclusions and ideas for further research and development

8.1 General conclusions
The current thesis is concerned with the construction processes of Jet Grouting, with a specific emphasis on two crucial themes required in a quality control programme: the diameter of the Jet Grouting elements and their achieved UCS strength. Various factors related to the Jet Grouting process have been described and discussed and then linked to the diameter and strength of the Jet Grouting elements.

A detailed description of the methods available in the global industry for measuring and estimating the diameter of Jet Grouting elements is presented together with the main issues concerning the strength. Using various case studies relating to the Thessaloniki Metro, an extended data analysis using graphs and charts was undertaken. The influence of the ground conditions and the soil type on the diameter and strength achieved was also examined.

Regarding the diameter issue, the methods were categorised into three main groups.

- Those where visual inspection takes place: **excavation and inclined coring**.
- Others where no visual check is possible or is not required: **thermic method**, where by measuring on site the temperature during the curing process of the binding agent (cement) in the center of the Jet Grouting column, the achieved diameter and the cement quantity in the column can be calculated. Jet Grouting column **callipers**, where the diameter can be calculated using mechanical devices directly after the construction of the column. **Painted bars**, where by assessing their erosion after the jetting process, the diameter achieved is estimated. **Hydrophones**, where based on certain signals the diameter is estimated. Calculation models based on the **specific weight of the spoil material**. Geophysical methods using sensitive electronics. Electric Cylinder® Method (CYLJET). **Wave Analysis Method**, where the evaluation of the diameter of the Jet Grouting column is obtained based on the use of a wave analysis approach.
- Those where the diameter is calculated based on theoretical approaches: (Turbulent Kinematic Flow Theory and Analytical Approach).

Assessing the available data for all the methods, the outcome shows that, apart from physically exposing the Jet Grouting elements, the most accurate method is to use inclined core drilling, whenever it is applicable. For example, based on author's experience, if the UCS strength of the Jet Grouting element is less than 3MPa or the native soil acquired a low compression strength $q_u$ without any gravel inside, then, it is possible that the core drilling process is not achieved with success. In addition, the appropriate equipment has to be utilised (diamond drilling head). Another method that provides an accurate scientific background and promising results is the thermic model: correlations were made between results using this technique and the coring method. The data analysis indicated that the
thermic model provides a conservative approach in sandy soil conditions (approximately 12% on the safe side), whereas optimistic values are likely to be obtained for clayey and silty ground conditions (approximately 12% higher values than in reality). The current accuracy, combined with the ongoing research on this method and its wide use in the Jet Grouting industry mean that there are further opportunities for improvement in the near future.

The thesis also describes how the diameter is influenced by the ranges of values of several factors and soil characteristics; for instance, the diameter is reduced when the lifting speed of the monitor is increased. Moreover, the diameter of an element is independent of the mean value of the unconfined compression strength considering UCS tests of wet samples. The role of the specific weight of the wet sampling material is something totally new in the Jet Grouting literature without any past experience worldwide. In sand and gravel environments, the diameter is generally reduced when the specific weight is increased whereas in clayey and silty areas, the diameter is not really influenced by the variation of the specific weight of wet sampling. Regarding the soil characteristics, the diameter achieved becomes smaller as the SPT values become higher (in all types of soil). It has been observed that the diameter is not influenced at all by the variation of qu in sandy conditions, whereas in silt and clay the higher the qu value the lower becomes the diameter.

The thesis also presents a mapping of the main factors that influence the Jet Grouting processes. Following from this, a new concept and approach was developed for estimating the diameter of a Jet Grouting element on site based on the main factors that influence its size involving the executional parameters, the equipment, the grout used and the soil conditions. Separating the examined cases in four clusters based on the lifting speed, the following empirical formulae were developed:

- \(10 \leq z \leq 15:\) \[D = -0.040 \times z + 0.861 \times \gamma_{JG} + 0.010 \times \text{SPT}\]
- \(15 \leq z \leq 20:\) \[D = 0.044 \times z + 0.615 \times \gamma_{JG} - 0.002 \times q_u + 0.001 \times \text{SPT}\]
- \(20 < z < 30:\) \[D = 0.046 \times z + 0.844 \times \gamma_{JG} - 0.003 \times q_u - 0.013 \times \text{SPT}\]
- \(30 \leq z:\) \[D = -0.012 \times z + 0.938 \gamma_{JG} + 0.002 \times q_u + 0.003 \times \text{SPT}\]

where

- \(D (m)\): diameter of Jet Grouting element;
- \(z (\text{cm/min})\): lifting speed;
- \(\gamma_{JG} (\text{t/m}^3)\): specific weight of Jet Grouting fresh element;
- \(q_u (kPa)\): unconfined compression strength of soil samples;
- \(\text{SPT}\): number of blows, (SPT N-value).

The absolute standard error of the above formulas is 0.11m.

As well as the diameter issue, the strength topic was also analysed in great detail. The thesis concentrates mainly on the wet sampling and coring methods of collecting samples.
Both ways were investigated and correlations between the UCS results from wet samples and cores were developed. It was explained how faster and more economic is the wet sampling method compared to the core drillings. In addition, the way that the mean value of wet sampling is influenced by various factors was examined; for instance, it was shown that an increase in the water/cement ratio reduces the achieved strength. Additionally, as for the diameter case, the role of the specific weight of wet sampling on the UCS strength was checked as well. For all soil conditions investigated, the strength was found to increase as the specific weight increased and with this influence being more intense in soil where sand and gravel are main soil types. The two points above imply that regular measurements of the specific weight of wet sampling (together with unconfined compression tests) can assist the Geotechnical Engineers to gain very quickly an impression about the UCS strength of the Jet Grouting element and to react, if necessary, by implementing contingency measures (e.g. setting a lower water/cement ratio). The wet sampling UCS strength was also influenced by the soil characteristics; regarding SPT, in any type of soil, the higher the N-values, the higher the achieved UCS strength. On the other hand, considering the $q_u$ values, in the mixed soil of silty sand with gravels (where sand is the main ingredient), the element strength gets lower when soil $q_u$ is increased. In cases where the clayey and silty material was in greater percentage than the sand, the UCS strength of wet sampling material was not influenced by the variation of the soil $q_u$ UCS strength.

The author suggests the wet sampling method for the strength assessment of the Jet Grouting body and focuses on the mean values of the tested samples for various water/cement ratios. The development of ‘KiT Factor A’ (Table 11) was the final outcome of the strength analysis; its use can assist Geotechnical Engineers in the application of a quality control programme for Jet Grouting projects.

8.2 Ideas and suggestions for further research and development

The author suggests the following ideas for further research.

**Diameter**

1. Development of similar empirical formulae for the diameter calculation (based on lifting speed clusters) for other countries. Further analysis can also be done of the current formulae to include information relating to the grain size distribution. In this way, the influence of the soil on the Jet Grouting diameter can be checked in greater detail and perhaps also from the accuracy of formulae can be improved.

2. Data collection from other Jet Grouting projects could help verify whether the suggested formulae continue to give accurate results or can be corrected. The more data available the better the accuracy of a model.

3. Investigation of all the available diameter measurement and control methods based on their application on more sites. Correlations, similar to thermic – coring methods, can be developed for all the models if there are available Jet Grouting data. Hence,
more diameter measurement and control methods can be examined and their accuracy checked.

4. Development of the same type of formulae (based on lifting speed clusters) but using the specific weight of spoil material instead of the one of wet sampling. Technically, it might be not the most appropriate variable since, in the Jet Grouting process, it is better to test material that forms part of the structural element than waste material produced as part of the column construction. An advantage of the measurement of spoil material is that it requires less time and cost than the wet sampling method and so it is worthwhile for this topic to be further investigated and developed.

5. Investigation of Lesnik’s model (specific weight of spoil material) in correlation with coring similar to what has been done with the thermic method.

6. Investigation of a new method which has been developed by the Company Keller Grundbau G.m.b.H since October 2012 and is currently applied on sites. This method is based on the painted bars where sensors are montaged on the top of them and it is acoustically checked the contact of the jetting energy with the bars. The evaluation of the results of this method leads to an assessment of the diameter of the Jet Grouting element.

**Strength**

7. Estimation of the quantity of cement that remains inside the column based on the specific weight of the test samples (either cores or wet samples).
8. Similar diagrams produced for wet sampling can be also developed for UCS values determined from cores.
9. Involvement of spoil samples in assessing the UCS strength; it is an easy and inexpensive approach and is perhaps conservative as the material inside the JG element acquires a higher strength value than the spoil material.
10. Execution of triaxial compression strength tests on wet samples and cores. Then, the elastic modules of the Jet Grouting element can be estimated along with the Poisson’s ratio.

Additionally, it would be useful and interesting to develop a Risk Assessment of the Jet Grouting processes including also the soil risks as well as the methods that have been described for the diameter control and the strength issue presents also interest for development.

Finally, the author, while working on some sites, noted cases where larger diameters were achieved with higher values of lifting speed, compared with those formed using low values of lifting speed. This would be an interesting issue to be investigated along with its correlation with the soil behaviour.
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

Bibliography

‘The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.’


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- Soilcrete, Jet Grouting Brochure. Keller Grundbau Ge.m.b.H.


Appendix

Explanation of the soil abbreviations that are mentioned in the current Appendix

<table>
<thead>
<tr>
<th>First and/or second letters</th>
<th>Symbol</th>
<th>Definition</th>
<th>Second letter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>gravel</td>
<td></td>
<td>P</td>
<td>poorly graded (uniform particle sizes)</td>
</tr>
<tr>
<td>S</td>
<td>sand</td>
<td></td>
<td>W</td>
<td>well graded (diversified particle sizes)</td>
</tr>
<tr>
<td>M</td>
<td>silt</td>
<td></td>
<td>H</td>
<td>high plasticity</td>
</tr>
<tr>
<td>C</td>
<td>clay</td>
<td></td>
<td>L</td>
<td>low plasticity</td>
</tr>
<tr>
<td>O</td>
<td>organic</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If the soil has 5–12% by weight of fines passing a #200 sieve (5% < P_{#200} < 12%), both grain size distribution and plasticity have a significant effect on the engineering properties of the soil, and dual notation may be used for the group symbol. For example, GW-GM corresponds to "well graded gravel with silt."

If the soil has more than 15% by weight retained on a #4 sieve (R_{#4} > 15%), there is a significant amount of gravel, and the suffix "with gravel" may be added to the group name, but the group symbol does not change. For example, SP-SM with gravel may refer to "poorly graded SAND with silt and gravel."

<table>
<thead>
<tr>
<th>Major divisions</th>
<th>Group symbol</th>
<th>Group name</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravel &gt; 50% of coarse fraction retained on No. 4 (4.75 mm) sieve</td>
<td>GW</td>
<td>well graded gravel, fine to coarse gravel</td>
</tr>
<tr>
<td>gravel with &gt;12% fines</td>
<td>GP</td>
<td>poorly graded gravel</td>
</tr>
<tr>
<td>sand ≥ 50% of coarse fraction passes No. 4 sieve</td>
<td>GM</td>
<td>silty gravel</td>
</tr>
<tr>
<td>clean sand</td>
<td>GC</td>
<td>clayey gravel</td>
</tr>
<tr>
<td>sand with &gt;12% fines</td>
<td>SW</td>
<td>well graded sand, fine to coarse sand</td>
</tr>
<tr>
<td>SP</td>
<td>poorly graded sand</td>
<td></td>
</tr>
<tr>
<td>silt and clay liquid limit &lt; 50</td>
<td>SM</td>
<td>silty sand</td>
</tr>
<tr>
<td>silt and clay liquid limit ≥ 50</td>
<td>SC</td>
<td>clayey sand</td>
</tr>
<tr>
<td>inorganic</td>
<td>ML</td>
<td>silt</td>
</tr>
<tr>
<td>organic</td>
<td>CL</td>
<td>clay</td>
</tr>
<tr>
<td>inorganic</td>
<td>OL</td>
<td>organic silt, organic clay</td>
</tr>
<tr>
<td>silt of high plasticity, elastic</td>
<td>MH</td>
<td></td>
</tr>
</tbody>
</table>
The control of column diameter and strength in Jet Grouting processes and the influence of ground conditions.

<table>
<thead>
<tr>
<th></th>
<th>silt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CH</strong></td>
<td>clay of high plasticity, fat clay</td>
</tr>
<tr>
<td><strong>OH</strong></td>
<td>organic clay, organic silt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Highly organic soils</th>
<th>Pt</th>
<th>peat</th>
</tr>
</thead>
</table>

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