GROUND IMPROVEMENT BY

JET GROUTING TECHNIQUES

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ABSTRACT

The main purpose of this Bachelor's thesis was to study the designing and construction process of soilcrete executed by various techniques of jet grouting. The thesis serves as a quick guide on understanding performance and limitations of improved soil, based on the jet grouting reported literature. Another aim of the thesis was to understand the execution and quality control process of various jet grouted projects that have been carried out in Finland.

In the first part of the thesis a general overview of Single fluid system, double fluid system, triple fluid system and their variations are presented. The engineering properties of soilcrete strongly depend on several parameters used. They are discussed in the second section of the thesis. The final part introduces the practice of jet grouting in Finland.

Although Jet grouting is an ideal ground modification technique compared to reinforcement and ground treatment method, the complex operation makes this technique limited in understanding the whole process precisely. To understand the jet grouting process properly the effects of several parameters on soilcrete's physical and mechanical properties should be studied carefully. Laboratory tests are recommended to estimate the theoretical values required for the designing process. It is also recommended to construct the trial soilcrete directly on the site before the main jet grout operation. since jet grouting construction is not visibly possible to control like in other construction, the state of art in quality control process requires a great deal of planning, monitoring and execution in every stage of construction process to achieve the desired outcome.

Keywords Ground improvement, jet grouting, soilcrete, Acoustic Column Inspector

Pages 56 pages including appendices 3 pages

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1 INTRODUCTION

Due to the increase in population lands are being used for residential and industrial purposes. As there are less availability of good ground for construction, ground improvement techniques are becoming the most effective way to make the land construction suitable both technically and economically. The objectives of land or soil improvement are to increase bearing capacity, shear strength, stability, stiffness and to prevent undesirable properties like liquefaction, settlements and swell by applying various techniques of geotechnical and construction engineering.

There are many ways and techniques to make unsuitable ground suitable for construction which can withstand larger forces. One of the techniques is jet grouting. The thesis serves as a quick guide on understanding the performance of improved ground, based on the jet grouting reported literature. The general idea is to understand the various applications, limitations and execution conditions of the jet grouting techniques to achieve the soil improvement objectives.

Jet grouting has been used for the underpinning work in many cases in Finland. Foundation restoration and excavations near buildings and structures are among the jet grouting projects cases in Finland. There are always risks of collapsing of soil which may cause a significant stress to foundation or substructures of building during the excavation close to the existing structure. Therefore, whenever there are existing structures nearby, jet grouting is a reasonable alternative to consider. It is also common to use jet grouting with other alternatives like sheet piles, micro piles, anchors or other construction parts. Another purpose of the thesis is also to find out about the execution and quality control process of jet grouted projects that have been carried out in Finland. For this purpose, the company KFS Finland Oy was visited.

2 GROUND IMPROVEMENT METHODS

Different kinds of improvement of the grounds can be achieved through various techniques and materials. Figure 1 below shows clearly the most commonly used techniques.

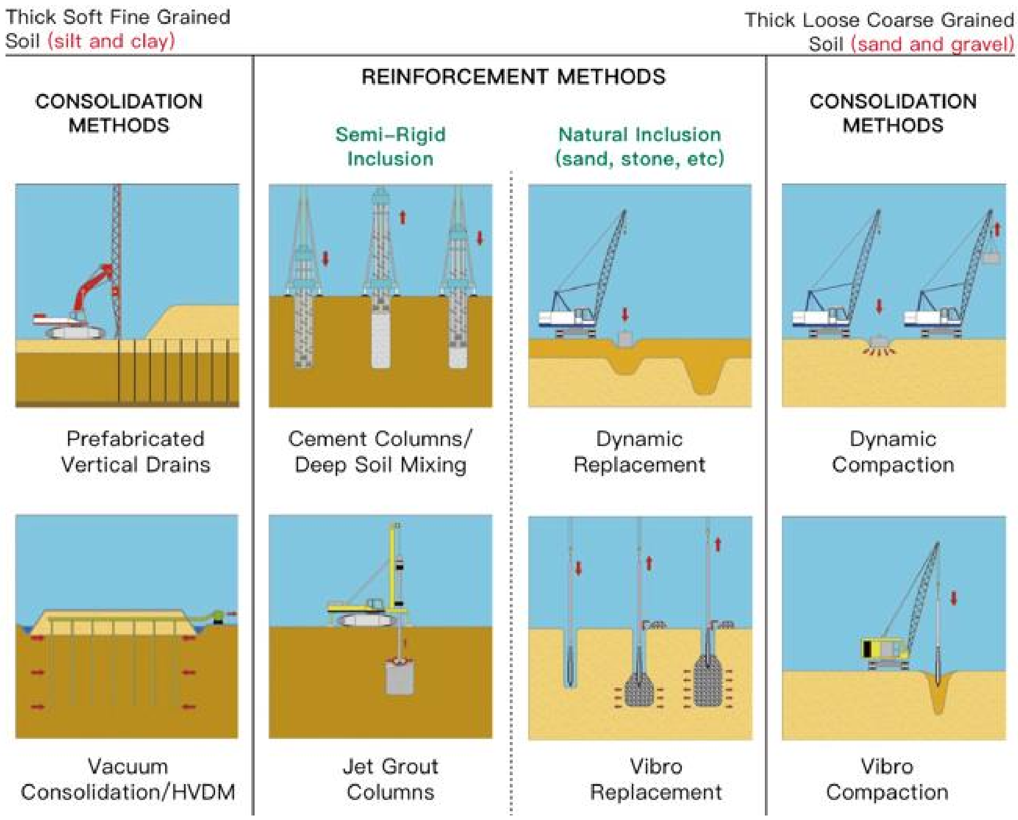


Figure 1. Ground improvement technique. (Geoharbour, 2017)

2.1 Densifications

The main purpose of densification is to give uniformity to the heterogenous granular soil. The method of densification is used to increase the strength, to prevent liquefaction and to reduce settlements of loose granular soil. The methods of densification are used commonly in loose granular soil, municipal waste soils and potential liquefiable soil. Dynamic compaction, vibro compaction, blast densification and compaction grouting are the most known techniques these days. However, this technique might have some restrictions on densely populated areas because of the large noise and the vibration that cause the negative influence on nearby structures and residents. (Kitazume & Terashi, 2013.)

2.2 Reinforcement

Reinforcement of soil can be done by inserting inclusions making the soil more reinforced so that the bearing capacity and shear strength can be achieved to the desired level. The constant development of this technique and selection of materials has advanced today to the level that allows to gain all the target engineering applications to withstand tension force, compression force and bending moments over the expected service life of the structure. Vibro replacement, compaction grouting, rigid inclusion, geosynthetic reinforcement have been some of the widely used reinforcement techniques in recent years. (Kitazume & Terashi, 2013.)

2.3 Chemical Modification

Chemical additives are the most commonly used methods to stabilize the soil enhancing their characteristic properties. Stabilizing soil with chemical additives using lime, cement fly ash, ground granulated blast furnace slag is common. Nowadays there are varieties of chemical binders in use and these binders are being developed; however, the most frequently used binders are lime and cement due to their cost and availability. Deep soil mixing, jet grouting and permeation grouting are some methods in chemical modification. (Mohammad & Abdullah, 2016.)

2.4 Other methods

Thermal stabilization is a process in which applied heating and freezing change the properties of soil. It is a well-known fact that under the ordinary temperature of the sun, the soil particles are improved. The soil can be heated from 300-100 degrees celsius artificially. Usually, this kind of application is useful in remediation of contaminated soils. This method is carried out by injecting heated air or steam into the contaminated soil through an injected well. In situ electric current is also applied to melt the soil in extreme heating. Thermal techniques are effective in soil containing organic, inorganic and radioactive materials. Freezing of the soil is applicable in temporary increase in strength for example, In excavation of tunnels and shafts. (Mohammad & Abdullah, 2016.)

2.5 Need for improvement

The loads of the structure are released to the soil layers through foundation. Therefore, it is very important to have solid ground to release the loads. The load which is coming through the foundation has to be released safely not only in static state but also in dynamic response. Therefore, it is very crucial that the capacity of the soil had to be strong enough to provide strong support in the long term without or minimal settlement. The properties of the ground therefore need to be verified if the loads can be transferred safely without any bearing or settlement issues. Soil foundation interaction, energy dissipation and the dynamic behaviour of structure should therefore be carefully studied. (Mohammad & Abdullah, 2016.)

2.5.1 Bearing capacity failure

The basic three types of bearing capacity failure are general shear failure, local shear failure and punching shear failure. In general shear failure, there is total separation of underlying soil. In local shear failure, there is separation of the soil below the footing. There is soil protruding on both sides of the footing, but the protruding is not as substantial as in general shear. In punching shear failure, there is an insignificant movement of soil on both sides of the footing and the soil outside the loaded area remains comparatively uninvolved. Figure 2 below shows the failures of bearing capacity. (Suryakanta, 2015.)

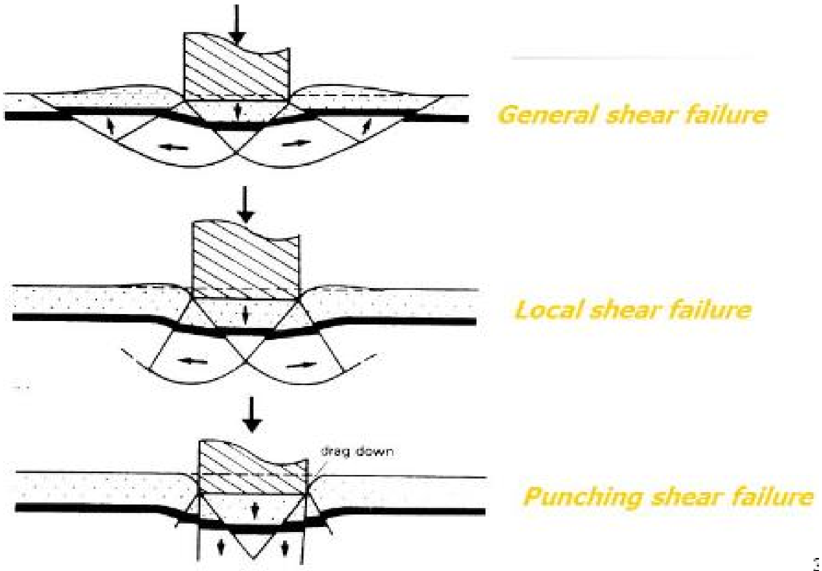


Figure 2. Bearing capacity failure

2.5.2 Settlement failure

The ground which is not compact and strong enough over time can be settled in different ways which give different possible results with the structures as shown in Figure 3 below. The first type of settlement is uniform in which the structure has just slipped inside the ground without any cracks. The second type is tipping settlement in which one side of the structure has more settlement than the other. In this kind of situation there are often no cracks. The third and the most dangerous settlement is differential settlement. In this type of settlement, the level of ground has settled differently in two or more parts resulting in the cracking in the structures. (Mishra, 2019.)

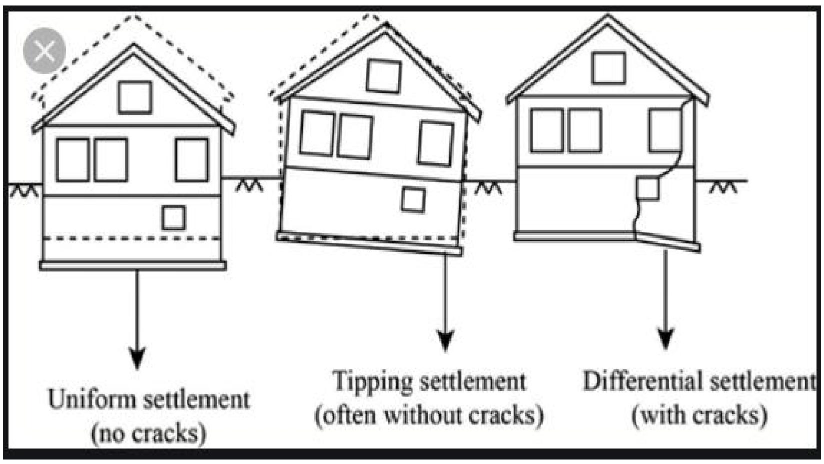


Figure 3. Settlement of structure. (Cheggstudy, 2019)

2.5.3 Liquefaction

Liquefaction is a phenomenon in which strength and stiffness of the soil is substantially reduced due to applied stress such as shaking during earthquake or other sudden change in stress condition. The shaking effect causes the water level to extent where the soil particles readily move with respect to each other. Liquefaction occurs in saturated or partially saturated soils. The factors required for liquefaction are loose granular sediments, water saturated sediments and strong shaking. (Mohammad & Abdullah, 2016.)

2.5.4 Slope stability

The weight of the slope is a driving force which is resisted by the strength of the soil along the slip surface is slope stability. Either static or seismic, the settlement in the slope or high embankment should always be considered with priorities. In the static state the settlement in one part can lead the slipping of the other part resulting in massive displacement. (Mohammad & Abdullah, 2016.)

3 JET GROUTING

Jet grouting is a recognized technique to stabilize soil by adding cement as a binder to form soilcrete which acts like a column itself and provides support to structure built on it. The principle in this technique is to erode the soil by applying high pressure water or water cement mix surrounded by air jets which erodes and loosen the soil in the boreholes which are mixed up with cement suspension to form soilcrete. Eroding distances vary depending on soil types and jet fluid used. The desired soilcrete of different geometrical dimensions and shapes can be achieved with various design. This stabilizing method can be used in almost all types of soil ranging from loose sediments to clay. Figure 4 shows the historical development of jet grouting method. (Ji, 2008.)

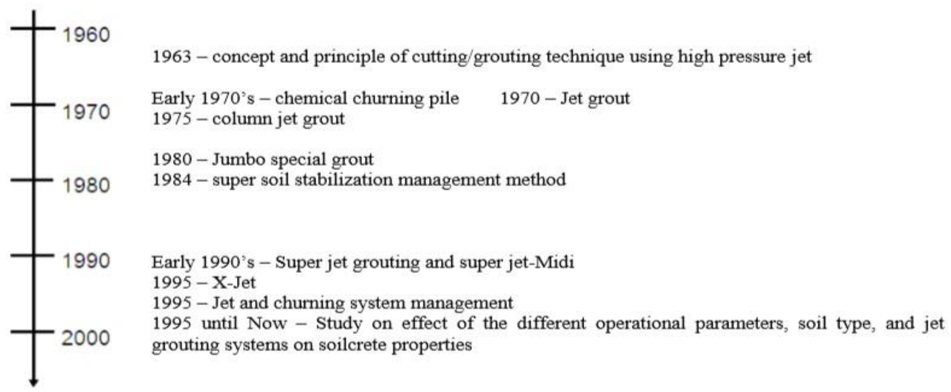


Figure 4. Historical development of jet grouting method (Ji, 2008)

3.1 Usual sites

One of the most distinct advantages of jet grouting is the possibility to improve most soils from soft clays and silts to sands and gravel regardless of soil types, permeability or grain size distribution. Soils which are non-homogenous and changing layer pattern including organic materials can be treated by jet grouting. The workability area of jet grouting is shown in Figure 5 and Figure 6. (Keller, 2017.)

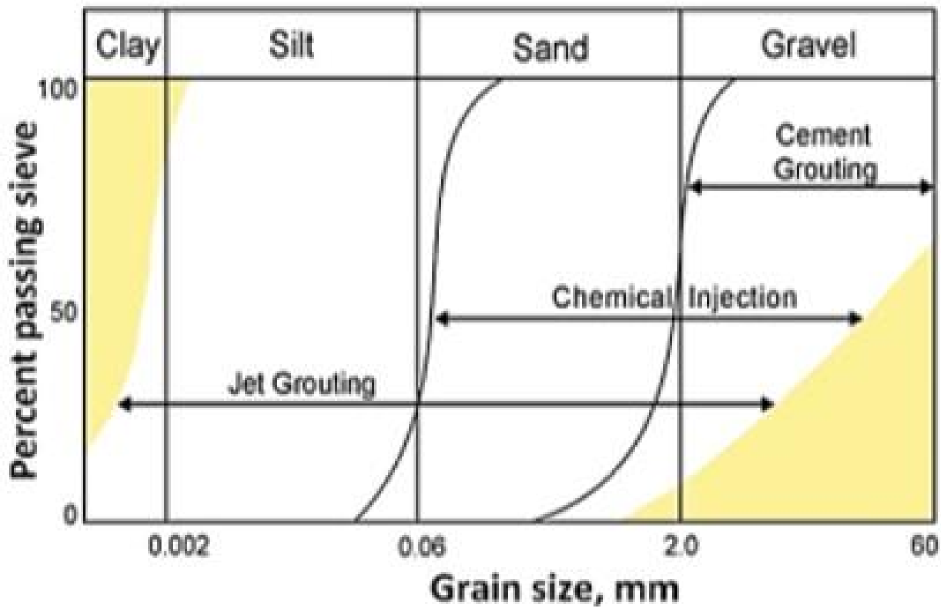


Figure 5. Jet grouting workability area (HBI, 2004)

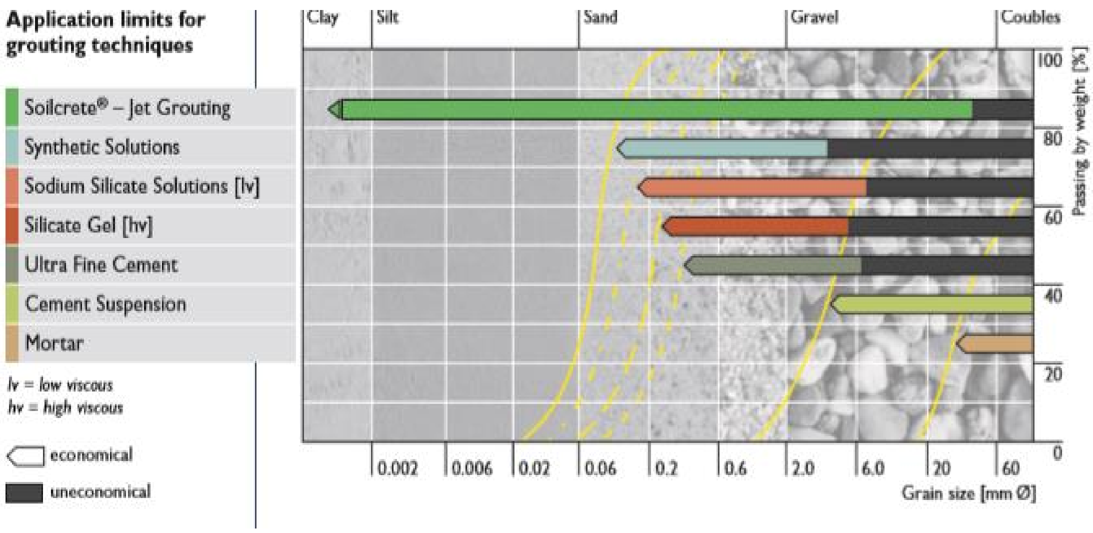


Figure 6. Application limits for grouting techniques (Keller, 2017)

3.2 Applications

Sometimes building has to be modify due to change in its utilization therefore, the modification is often required in the foundation. Soilcrete is an economic and flexible way to modify and support the foundation. Because of the phenomena of settlement, historical buildings may need the foundation restoration; in this case soilcrete provides safe and maximum structural protection to the foundation. Soilcrete can also be constructed horizontally or in slightly inclined angle which will protect and provide the stability to the loose soil around the tunnel area. In shock sensitive and urban environment areas nearby existing structures often require careful treatment of the soil to protect the foundation and give extra load bearing capacity. Soilcrete can be constructed next to structures which are exposed to earth pressure such as historical walls, steeplopes, avalanche protection etc. to reduce the stress. It also acts as a backup. In protection of tunnel usually in loose soil, soilcrete can be constructed under the tunnel and its surrounding soils. It also helps to reduce the groundwater penetration during the tunnel excavation. Even in confined working space a low density gravity wall can be safely constructed. In case of construction demand which requires vibration free installation or where shaft has to enter the ground water level, soilcrete of intersecting columns construction are widely used. Single or multiple soilcrete panel walls can be constructed to cut off the ground water level under the buildings or roads in the excavation process. Intersecting soilcrete columns can be constructed if there is a risk of higher mechanical strain by shear force, danger of undermining or high permeability requirements. Soilcrete can act as a sealing cover to protect the groundwater in case of construction activities. In many cases it can act like a joint sealing between the piles, sheet piles or other construction parts in the ground. Soilcrete slabs can be constructed to prevent uplift water pressure in pits and shafts of the small buildings. Typical areas of application and various jet grouting applications are shown in Figure 7 and Figure 8. (Keller, 2017.)

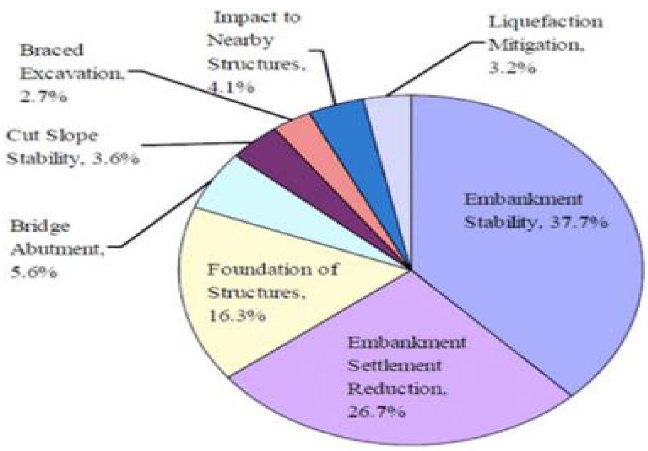


Figure 7. Typical areas of application for deep mixing method (Abbey & Ngambi, 2015)

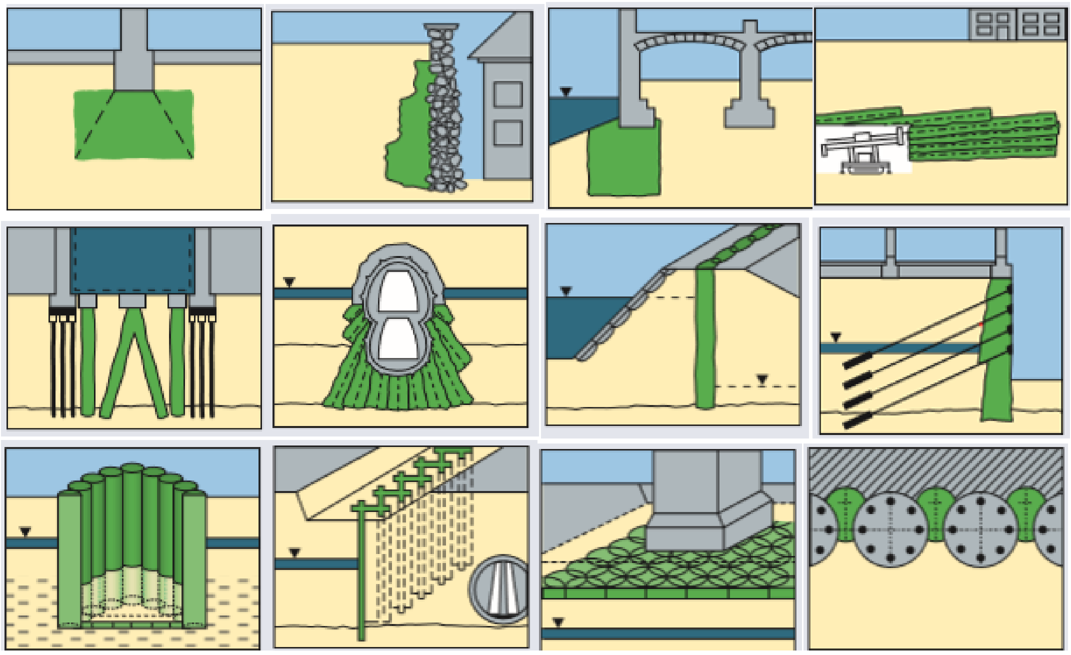


Figure 8. Jet grouting applications (Keller, 2017)

3.3 Advantages and disadvantages

Due to the several advantages, nowadays jet grouting techniques are being more widely used in construction projects than before. Jet grouting can be applied to almost all types of soil, which is its biggest advantage. From gravel to clay jet grouting can be executed. With comparing alternative methods, jet grouting is the fastest, safest and most direct method. Due to the selection opportunity of large variety of machinery choice it can be applicable in a limited working space as shown in Figure 9. The Possibility of different geometrical soilcrete can be achieved with this technique, for example, full column, half column, quarter column and panels. Soilcrete is always maintenance free and can applied to the specific layer of the soil to be treated with control monitoring. Soilcrete can be used with sheet piles, micro piles, anchors and other construction methods in the same project. Advantages and disadvantages with the choice of different fluid system is listed by Burke (2004) in Table 1.

Table 1. Advantages and disadvantages of jet grouting (Burke, 2004)

System	Advantages	Disadvantages
Single Fluid	-Simplest system and equipment -Good to seal vertical joints -Good in cohesionless soil	-Smallest geometry created -Hardest to control heave -Difficult to control quality in cohesive soils
Double Fluid	-Most utilized system -Availability of equipment and tooling -High energy, good geometry achieved -Most experience -Often most economical	-Very difficult to control heave in cohesive soils -Spoil handling can be difficult -Not usually considered for underpinning
Triple Fluid	-Most controllable system -Highest quality in difficult soils -Best underpinning system -Easiest to control spoil and heave	-Complex system and equipment -Requires significant experience
Super Jet	-Lowest cost per volume treated -Best mixing achieved	-Requires special equipment and tooling -Difficult to control heave in cohesive soils -Spoil handling difficult -Cannot work near surface without support -Highest logistical problems
X-Jet	-Confidence of geometry -Controllable materials cost -Best for soft cohesive soils	-Very specialized equipment that requires daily calibration -Limited experience available

Figure 9. Jet grouting in confined space (Keller, 2017)

One of the major disadvantages of jet grouting is to control the heave in the cohesive soil. The spoil material returns during the grouting process will lead to the ground heave if not handled properly. Therefore, it is very important in the jet grouting process to control the spoil return properly. Several authors have studied the effects of jet grouting on the adjacent ground and structures which cause significant lateral ground movement due to ground heave. In the studies performed by Pinto et al, (2013), it was concluded that the lateral ground movement was observed in a historic old south church because of soil displacement during jet grouting process possible due to the lack of proper spoil return or large injection pressure. Similarly, in another study conducted by Poh & Wong (2000), the results of monitoring suggest that jet grouting was the reason for the retaining diaphragm walls to move. It also induced some bending movement on the diaphragm walls causing the adjacent structure tilt and move away from jet grouted area. The field study conducted by Wu et al., (2016) on Lianyan and Linhai highway in China, shows that the ground heave of 219 mm was induced shortly after the construction in Lianyan highway. The large ground heave was measured in Linhai highway which is 337 mm. Based on adopted analytical method it was concluded that the ground heave increased with grout pressure but decreased as the embankment load and distance from the pile centre increased. Figure 10 shows the ground heave on the Linhai highway which leads to the cracking along the longitudinal direction of embankment.

Figure 10. Crack due to jet grouting on the Linhai Highway (Wu, 2016)

3.4 Machinery

A large set of machinery is needed to perform jet grouting. These sets of machinery can be divided into fixed station and moveable drilling rig. The fixed station consists of a cement silo, water tank, mixer unit, storage tank, pump unit and air compressor. The cement silo is a storage unit of large quantity of cement which has capacity to supply the need of jet grouting mixture. Cement and water are mixed in the mixer unit where cement slurry is prepared. The desired ratio of water to cement can be measured and set electronically in this mixer unit. The prepared cement slurry passes to the storage tank and from storage tank to pump unit. The grout is then pumped with the desired pressure to the drilling rig. The moveable drilling rig consists of pipelines to spread high pressure grout, air and water coming from the fixed station. Usually the space required for the jet system plant installation is 120 to 200 m^2. The construction sequence of jet grouting is shown in Figure 11. (Keller, 2017; Kitazume & Terashi, 2013.)

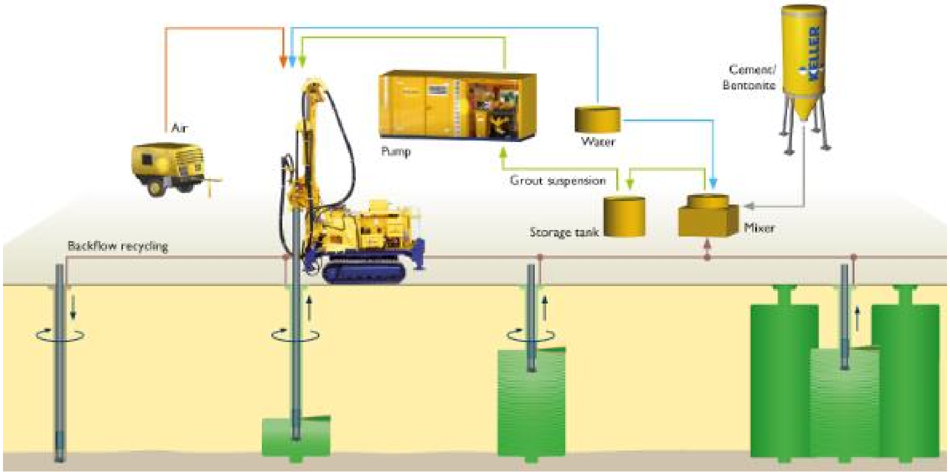


Figure 11. Construction sequence (Keller, 2017)

3.5 Materials and cement hydration mechanism

The mixture of cement and water is usually used in the jet grouting process. Ordinary Portland cement, high early strength Portland cement and blast furnace slag are widely used in the stabilization process. Ordinary Portland cement is a mixture of gypsum and cement clinkers. Cement clinkers are made formed by the minerals $3CaO{\cdot}SiO_2$, $2CaO{\cdot}SiO_3$, $3CaO{\cdot}Al_2O_3$ and $4CaO{\cdot}A_{l2}O_3{\cdot}Fe_2O_3$. Lime and lime based special binders are also common in the soil stabilizing process. Quick lime (calcium Oxide), slaked lime (calcium hydroxide), wet hydroxide and lime based special binders are some commonly used materials. Wet hydroxide is a mixture of hydrated lime and 20-25% of water whereas lime based special binders are a mixture of quick lime or hydrated lime as the main materials and gypsum, slag or fly ash. Other materials such as bentonite, filler, water reducing, plasticising, waterproofing or anti-washing admixtures can be added to the mix. The water to cement ratio by weight should range between 0.5 to 1.5. Any potable water can be used in making of grout mixture. Water other than recognised potable water should be tested to ensure that will not affect to the settling, hardening or durability of mixed and will not stimulate corrosion of the reinforcement. (BS EN12716,2001.)

In the reaction shown in Figure 12, a cement mineral, for example, $3CaO.SiO_2$ reacts with water to produce cement hydration products. The cement hydration product has high strength which increases over the age, whereas the production of calcium hydroxide contributes to the pozzolanic reactions in the lime stabilization process.

$$6(3CaO{\cdot}SiO_2) + 6H_2O = 3CaO{\cdot}2SiO_2{\cdot}3H_2O + 3Ca(OH)_2.$$

Saitoh et al., (1985) has presented the complicated cement hydration mechanism in a simplified form as shown in Figure 12.

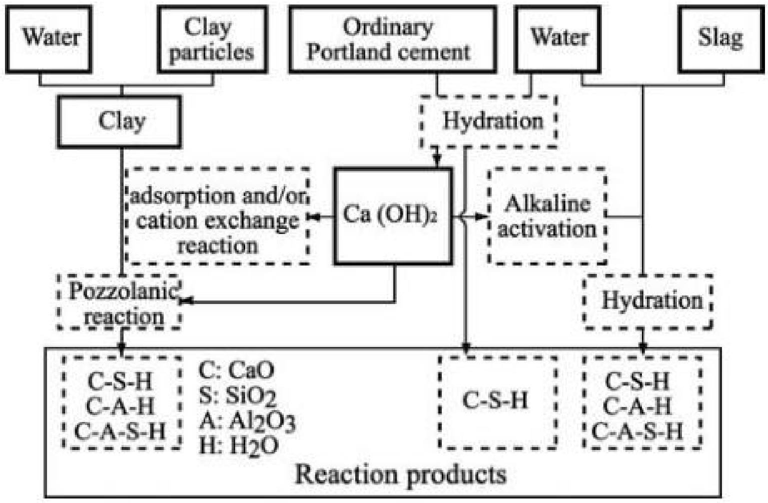


Figure 12. Chemical reaction between clay, cement, slag and water (Saitoh et al., 1985)

3.6 Techniques

Various techniques are used to make soilcrete on sites. The selection of the technique depends on soil condition, geometrical form and the needed soilcrete quality. The techniques include drilling, jetting, grouting and extension which are discussed below.

GI machines are used in the first place to start the jet grouting hole. The drilling rod which is equipped with the jet nozzle and drill bit are used to drill the jet grouting hole to the desired depth. Special drilling rods can be used in case of concrete and masonry. Drilling can be done perpendicular or at an inclined angle depending upon the design. The special care should be taken in case of any nearby structures which can liquefaction the surrounding soil resulting by vibration of the drilling. (Kitazume & Terashi, 2013.)

From the lower end of the desired soilcrete, high pressure jet (water, air, or combination of both) is used to erode the soil particles. The excess amount of water, soil and cement mixture (spoil) is removed from the surface between the bore hole and the drilled rod (annulus). This process is constantly monitored because the spoil flow should be smooth and continuous to prevent excessive pressure build up. If the uplift velocity is not greater enough to exhaust the spoil to the surface the annulus can be plugged which acts as a passive pressure to the soil resulting in poor soilcrete quality, geometry and ground surface heaving. (Schaefer, 1997; Ji, 2008.)

Grouting is done simultaneously with the process of jetting i.e, erosion of the soil. Depending on the soilcrete property various cement suspension can be injected. Due to the vibration caused by the jetting rod, the uniform mixture of jetting grout and the soil is possible within the treatment zone. Jetting and grouting start from the low end of the soilcrete and are slowly lifted upward up to the top of the soilcrete. (Liikennevirasto, 2018.)

Extension of soilcrete is a repetition process; however, the extension sequences depend on the condition and the technical requirements of the structures to be treated. Soilcrete elements can be constructed fresh on fresh or fresh against firm which can be done in various ways. (Liikennevirasto, 2018.)

3.7 Single fluid System

Single fluid system is the simplest system in which the only binder slurry is injected through the small nozzle with high pressure and mixed with in-situ soil to form soilcrete. This system operates with grout jet of minimum 100m/s exit velocity which erodes and cuts the soil without air shroud. This system is suitable in cohesionless soil and allows for small to medium sized soilcrete construction. The single fluid system releases least amount of energy to the ground therefore producing the least amount of spoil. This system should be considered if there should not be any spoil return during the construction in the work site. The single fluid system is shown in Figure 13. The design values and standard operational parameters for single fluid system is shown in Table 2 and 3.

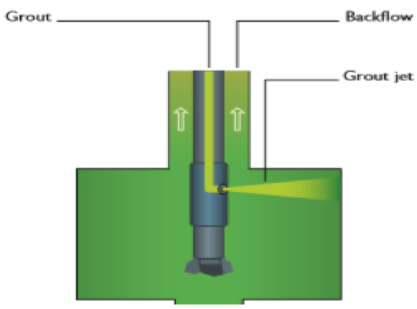


Figure 13. Single fluid system (Keller, 2017)

Table 2. Design values of Single fluid system (JJGA, 2011)

Binder type	soil	W/C ratio	q_u (MN/m^2)	cohesion, c (MN/m^2)	adhesion (MN/m^2)	bending strength (MN/m^2)	elastic modulus (MN/m^2)
CCP5	sand	90%	1.0	$1/6\ q_u$	c/3	2c/3	$100\ q_u$
	clay		0.8				
	organic		0.2				
CCP-6	sand	100%	3.0				
	clay		1.0				
CCP-7A	sand	150%	2.0				
	clay		0.5				
CCP-7B	sand	110%	1.0				
	clay		0.5				
CCP-8	organic	100%	0.3				

Table 3. Standard operational parameters for single fluid system (JJGA, 2011)

(a) For sand layer.

SPT N-value of original soil	*N < 5*	*5 < N < 10*	*10 < N < 15*
Binder injection pressure (MN/m²)	20.0	20.0	20.0
Withdrawal speed (m/min.)	0.25	0.25	0.25
Rotation speed (rpm)	20	20	20
Flow rate of binder slurry (m³/min.)	0.035	0.035	0.035
Diameter of column (m)	0.40	0.35	0.30

(b) For clay layer.

Cohesion of original soil (kN/m²)	*C < 10*	*10 < C < 30*	*30 < C < 50*
Binder injection pressure (MN/m²)	20.0	20.0	20.0
Withdrawal speed (m/min.)	0.25	0.25	0.25
Rotation speed (rpm)	20	20	20
Flow rate of binder slurry (m³/min.)	0.035	0.035	0.035
Diameter of column (m)	0.50	0.45	0.30

3.8 Double fluid System

In double jet system air and binder slurry are used. This technique is the progression of single fluid system to enhance the cutting radius with shroud of compressed air and binder as shown in Figure 14 below. Double fluid system is more effective in penetrating cohesive soil compared to the single fluid system. The blinder slurry is injected at a minimum of 20MN/m^2 exit velocity for eroding and cutting of the soil. To increase the cutting capacity and range of the grout high velocity air compression pressure of 0.7MN/m^2 is used through the air jet nozzle. The air compression helps to binder slurry to travel further from the injecting nozzle therefore creating a larger soilcrete diameter than the single fluid system. Due to the air lifting effect created by air compression more slime is produced comparing to the single fluid system. The binder slurry is prepared in the mixture and transferred to the injection machine through a hydraulic pump and injected to the ground. The injecting pipe is a duplex cylinder usually 60.5mm in outer diameter. On the bottom of the pipe two injection nozzles are installed side by side to inject binder slurry horizontally. The capacity of the water tanks and pumping units are usually bigger compared to single and double jet techniques. Water tanks of 5m^3 and pumping units of 12m^3/h are typically used. (Kitazume & Terashi, 2013.)

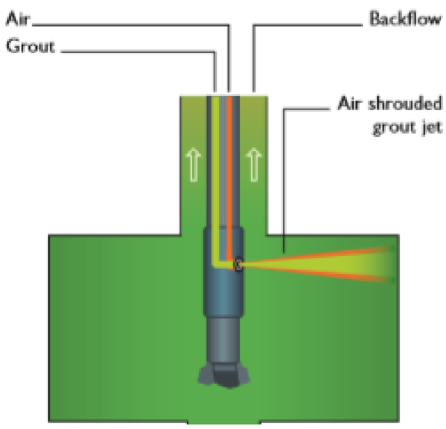


Figure 14. Double fluid system (Keller, 2017)

The following equation 1 gives the required amount of binder slurry needed to stabilize the soilcrete.
Where,

$Q = H \cdot \nu \cdot q_C \cdot (1+\beta)$ (1)

Q: Total volume of binder slurry
H: length of soilcrete column (m)
q_C: Flow rate of binder slurry (m^3/min)
ν: Time required for injection per unit length (min/m)
β: Coefficient (0.06)

During the construction a large amount of slime is produced which is lifted along the injection pipe and must be removed. This amount of slime can be estimated by the following equations.

V= V1+V2 (2)

V1= $(q_c + q_w) \cdot H \cdot v \cdot (1+\alpha)$ (3)

V2= $\sum t \cdot q \cdot y$ (4)

Where,
V: volume of slime (m^3)
V1: volume of slime due to column construction (m^3)
V2: volume of slime due to drilling (m^3)
q: flow rate of drilling pump (m^3/min)
q_w: flow rate of high-pressured water (m^3/min)
t: time required for injection per unit length (min/m)
α: coefficient

Table 4. Execution condition (JJGA, 2011)

	Double fluid system	Triple fluid system
q	0.04 m^3/min.	0.2 m^3/min.
q_c	0.06 m^3/min.	0.14 or 0.18 m^3/min.
q_w	0 m^3/min.	0.07 m^3/min.
α for sand	0.1	0.1
for clay	0.3	0.15
γ	0.5	0.2

Table 5. Design value of Double fluid system (JJGA, 2011)

Binder type	soil	W/C ratio	q_u (MN/m^2)	cohesion, c (MN/m^2)	adhesion (MN/m^2)	bending strength (MN/m^2)	elastic modulus (MN/m^2)
JG-1	sand	100%	3.0	0.5	c/3	2c/3	300
JG-1	clay	100%	1.0	0.3			100
JG-2	sand	150%	2.0	0.4			200
JG-3	sand	200%	1.0	0.2			100
JG-4	organic	100%	0.3	0.1			30
JG-5	clay	150%	1.0	0.3			100

3.8.1 Superjet System

Superjet system in itself is a double fluid system which is used to make the soilcrete of larger diameter up to 5 m. Binder slurry is injected at a high pressure of 30MN/m^2 which is added by high compression air of 0.7MN/m^2 to 1.05MN/m^2 which shrouds the binder slurry. Because of the reduced friction due to air, binder slurry can travel farther from the injection point producing stabilized soilcrete of greater diameter. The binder slurry is prepared in the mixture and transferred to the injection machine through a hydraulic pump and injected to the ground. The injecting pipe is a duplex cylinder usually 140mm in outer diameter. On the bottom of the pipe two injection nozzles are installed side by side to inject the binder slurry horizontally. Figure 15 contains a picture of superjet system. The capacity of the water tanks and pumping units are usually bigger compared to single and double jet techniques. Water tanks of 60m^3 and pumping units of 36m^3/h are typically used. Station set up required 200 m^2. (Kitazume & Terashi, 2013, 263.)

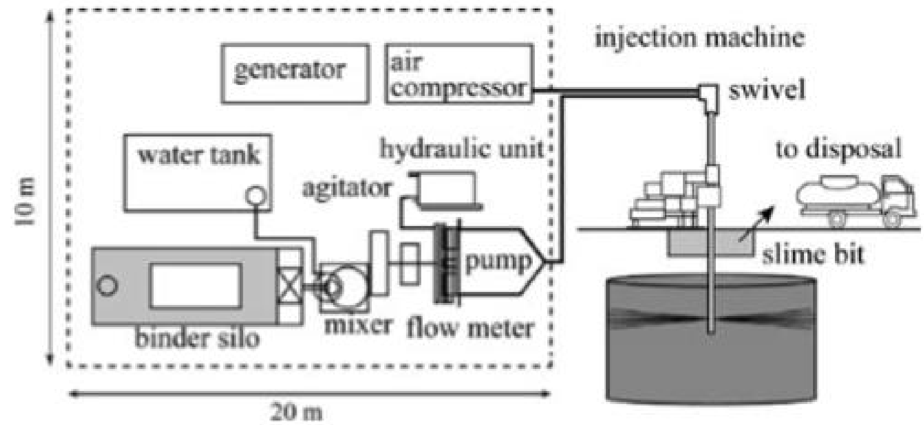


Figure 15. Layout of Superjet system (Superjet Association, 2011)

3.9 Triple Fluid System

Triple fluid system consists of binding slurry, air and water. The water is injected at a high pressure aided by the high velocity of compressive air through the air and water nozzle. The binding slurry is injected through the separate hole below the air and water nozzle to fill the void created by air lifting effect. To erode the soil, high pressured water of 40MN/m^2 and air velocity of 0.7MN/m^2 are injected. At the same time binding slurry at a pressure of 2 to 5 MN/m^2 is injected through the nozzle located below the air water nozzle. The minimum pressure of grout pump is above 15 bar in this system. This system is mainly used to treat the cohesive soil. (Kitazume & Terashi, 2013.) Comparing to the single fluid and double fluid system the replacement of degree of soil is relatively high considered by some as a full replacement. Specially in silty and clayey soil the degree of replacement is high. As a result the soilcrete made using this technique typically has high strength compared to soilcrete made by single fluid and double fluid system. The soilcrete made using triple fluid system also has more homogenous soil cement composition compared to single fluid and triple fluid system. (Powers et al.,2007.) Triple fluid system is shown in Figure 16. Table 6 and 7 shows the design values and the execution conditions.

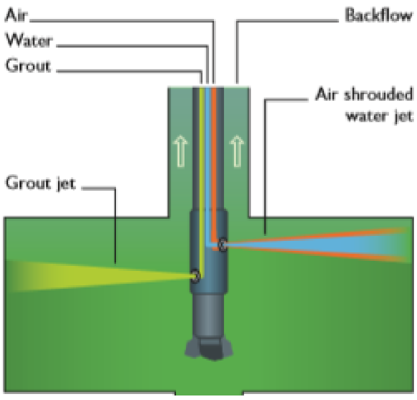


Figure 16. Triple jet system (Keller, 2017)

Table 6. design values of Triple fluid system (JJGA, 2011)

Binder type	*soil*	q_u *(MN/m²)*	*cohesion, c (MN/m²)*	*adhesion (MN/m²)*	*bending strength (MN/m²)*	*elastic modulus (MN/m²)*
JG-1	sand	3	0.5	c/3	2c/3	300
JG-1	clay	1	0.3			100
JG-2	sand	2	0.4			200
JG-3	sand	1	0.2			100
JG-4	organic	0.3	0.1			30
JG-5	clay	1	0.3			100

Table 7. Execution condition for Triple fluid system (JJGA, 2011)

(a) For sand layer

SPT N-value of original soil	*N < 30*	*30 < N < 50*	*50 < N < 100*	*100 < N < 150*	*150 < N < 175*	*175 < N < 200*
Water injection pressure (MN/m²)	40	40	40	40	40	40
Air pressure (MN/m²)	0.7	0.7	0.7	0.7	0.7	0.7
Binder injection pressure (MN/m²)	2 to 5	2 to 5	2 to 5	2 to 5	2 to 5	2 to 5
Withdrawal speed (m/min.)	0.0625	0.05	0.05	0.04	0.04	0.04
Rotation speed (rpm)	20	20	20	20	20	20
Flow rate of binder slurry (m³/min.)	0.18	0.18	0.16	0.14	0.14	0.14
Diameter of column (m)	2.0	2.0	1.8	1.6	1.4	1.2

(b) For clay layer

SPT N-value of original soil	*N < 3*	*3 < N < 5*	*5 < N < 7*	*7 < N < 9*
Water injection pressure (MN/m²)	40	40	40	40
Air pressure (MN/m²)	0.7	0.7	0.7	0.7
Binder injection pressure (MN/m²)	2 to 5	2 to 5	2 to 5	2 to 5
Withdrawal speed (m/min.)	0.05	0.05	0.04	0.04
Rotation speed (rpm)	20	20	20	20
Flow rate of binder slurry (m³/min.)	0.18	0.16	0.14	0.14
Diameter of column (m)	2.0	1.8	1.6	1.2

3.9.1 X-jet system

X-jet system is the triple fluid system in which high pressure water of 40MN/m^2 an air pressure of 0.6 MN/m^2 to 1.05MN/m^2 are injected by two nozzles on the side surface of the injecting pipe. The two injecting jets collides each other at predetermined diameter to erode the soil at desired distance as shown in Figure 17. The binder slurry is prepared in mixture and transferred to the injection machine by a hydraulic pump. The triple cylinder Injection pipe of having 90 mm outer diameter is used in this technique. There are three nozzles installed on the side surface of the pipe near the bottom. The upper two nozzles are for injecting high pressured water and air and the lower third nozzle is for injecting binder slurry. Table 8 shows the design values for sandy soil by x-jet system. (X-jet Association, 2011.)

Table 8. Design values for sandy soil (X-jet Association, 2011)

Binder type	soil	W/C ratio	q_u (MN/m^2)	cohesion, c (MN/m^2)	adhesion (MN/m^2)	bending strength (MN/m^2)	elastic modulus (MN/m^2)
CROSSSAND	sand	75%	3	0.5	c/3	2c/3	300
CROSSSAND	sand	75%	2	0.4			200
CROSSNEN	clay	100%	1	0.3			100
CROSSNEN	organic	100%	0.3	0.1			30

Figure 17. Injection of water jets from tip of X-jet system (X-jet Association, 2011)

3.9.2 Twin jet system

Twin jet system is the advanced version of the traditional triple fluid system which is used for the instant solidification of soft ground by adding a binder in the admixture. The principle in this technique is to accelerate the hardening process between the soft soil and the grout in the presence of sodium silicate (water glass) as a binder. The admixture of grout and soil can be gelled within 5 to 10 seconds. In this technique firstly the high-pressure grout shrouded by compressive air erodes the soil to form an admixture of grout and soil. Then the high-pressure grout shrouded by sodium silicate solution is jetted into the admixture to form quick gelled soilcrete. According to the case study of twin jet techniques by Wang et.al, (2013) concluded that this technique is simple to operate with low cost and enhancing work efficiency up to three times. The twin jet system can be implemented successfully in sandy soil with excellent uniformity in the column diameter. The twin jet system is more beneficial in horizontal jet grouting applications than vertical jet grouting. However, the study also showed that the lateral soil displacement due to the construction of soilcrete by this technique was large up to 260 mm. Figure 18 below shows the illustration of soilcrete formation with twin jet system. (Wang et.al, 2013.)

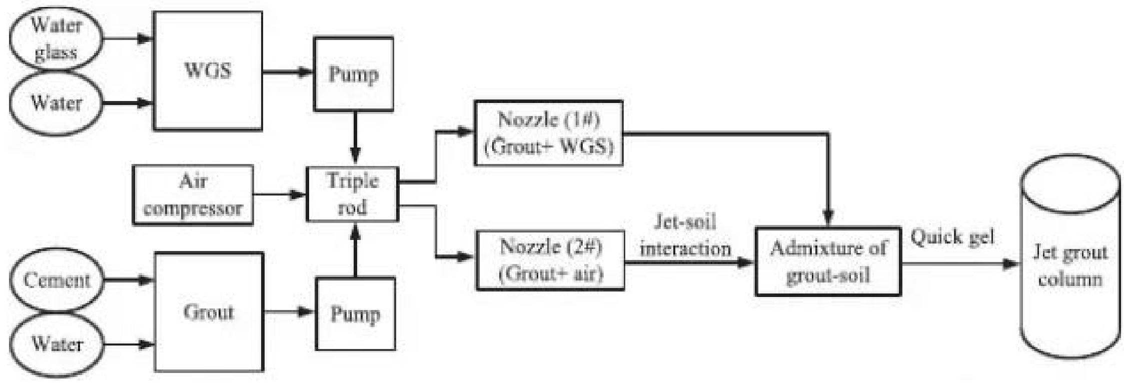


Figure 18. Illustration of formation of jet grout column with twin jet method (Wang et.al, 2013)

4 DESIGN OF JET GROUTING

4.1 Eurocode 7 Geotechnical Design

Design and detailing of geotechnical structures are governed by European standards. Eurocode 7 is a European standard for the underground construction SFS-EN 12716: 2001, which has partly been the basis for this guidance. (Eurocode-7/2013; SFS-EN 12716/2001). Table 9 shows the range of jet grouting parameters.

Table 9. Range of jet grouting parameters (BS EN12716,2000; Page 28)

Annex B
(informative)

Ranges of jet grouting parameters

The jet grouting parameters usually adopted for the different systems fall within the following ranges :

Jet grouting parameters		Single fluid	Double fluid (air)	Double fluid (water)	Triple fluid
Grout pressure	(MPa)	30 to 50	30 to 50	> 2	> 2
Grout flow rate	(l/min)	50 to 450	50 to 450	50 to 200	50 to 200
Water pressure	(MPa)	N/A	N/A	30 to 60	30 to 60
Water flow rate	(l/min)	N/A	N/A	50 to 150	50 to 150
Air pressure	(MPa)	N/A	0,2 to 1,7	N/A	0,2 to 1,7
Air flow rate	(m^3/min)	N/A	3 to 12	N/A	3 to 12
N/A Not applicable.					

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.

4.2 Finnish Transport Infrastructure Agency

Although the base structures and bottom reinforcements are done according to the Eurocode system, jet grouting is treated only on a general level in Eurocode. The European standard for the construction of underground construction is SFS-EN 12716: 2001, which has partly been the basis for this guidance. The design and dimensioning of jet grouting injections has traditionally been made in Finland to a great extent from experience. (Liikennevirasto, 2018.)

According to the Liikennevirasto (2018), the German standard DIN 4093 has been used as a source for designing and dimensioning section of column boundary measurement.

4.3 Physical Properties of Soilcrete

The geometrical property of soilcrete is executed by the movement of the drill rod. Half column, quarter column and full column can be executed with the actions of rotation and pulling of the drill rod. When the drill rod is simply pulled without any rotation, panels are created. A complete column is constructed if the rod is pulled and rotated. Similarly, with the half rotation and pulling, a half column is made. The two basic types of soilcrete schemes set by the EN12716:2001 are shown below in Figure 19 and 20.

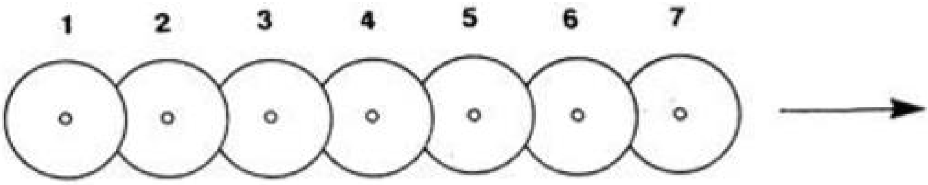


Figure 19. Fresh in fresh sequence (BS EN12716,2001)

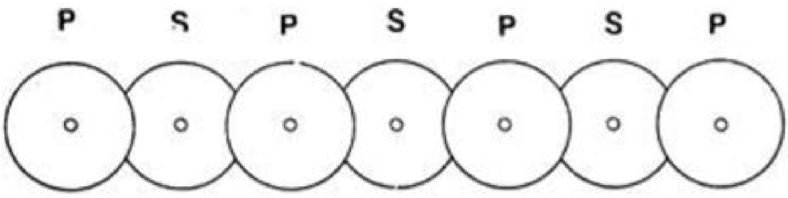


Figure 20. primary – Secondary sequence (BS EN12716,2001)

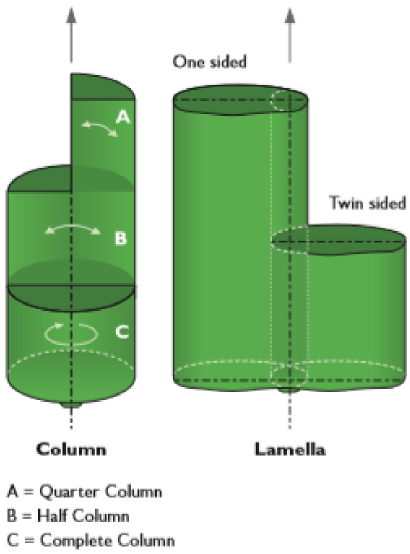


Figure 21. Geometry of soilcrete (Keller-krate)

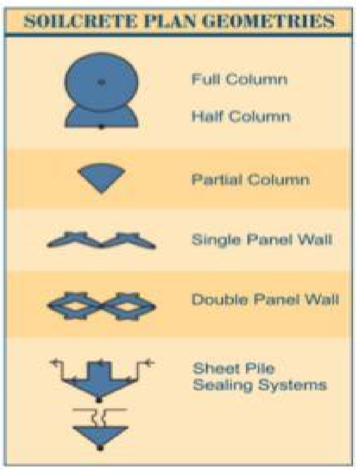


Figure 22. Soilcrete different geometry (HBI 2004; Schaefer 1997)

4.3.1 Physical properties

The main purpose of the stabilization of the soil is to lower the water content amount than the original soil subgrade with binders making them more stable. This can be achieved by mixing a very small amount of binder with respect to the dry weight of the soil to change the physical properties of soil. Engineering properties of lime and cement stabilized clay and sands have been extensively studied and examined in detail in Japan. Although the strength gain by stabilized soil depends on various factors, the engineering properties of both cement stabilized soil and lime stabilized soil are quite similar. The soils which are treated wet mixing in Japan are of very soft dredge clay, organic soil, soft alluvial soil usually having water content nearly equal or exceeding their liquid limits. The result of experiment conducted by Nikbakhtan & Osanloo is presented below in Table 10 which shows the difference in mechanical properties of soil and soilcrete. (Kitazume & Terashi, 2013.)

Table 10. Comparison of physical and mechanical properties of soil and soilcrete (Nikbakhtan & Osanloo)

	Before jet grouting	After jet grouting
UCS (MPa)	0.025-0.05	2.4
C (KPa)	40	770
φ (degree)	0	25
Water content (%)	38	50-75
σ_t (KPa)	3.75-7.5	645

4.3.2 Change of water content

Estimation of water content on cement stabilization soil after the hydration reaction can be given as

$$w_s = \frac{w_0 + (\beta - \lambda) \cdot aw}{100 + (1 + \lambda) \cdot aw} \cdot 100 \qquad (5)$$

Where,
w_0: water content of original soil (%)
w_s: water content of stabilized soil (%)
aw: binder factor (%)
β: water binder ratio (%)
λ: water ratio for cement hydration (0.25 to 0.28 of dry weight of cement)

The ordinary Portland cement with binder content (aw) of 5 %,10 %,15 % and 20 % was used to stabilise with singawaga clay (w_L of 62.6%, w_p of 23.1% and w_i of 76.5%). The result in Figure 23 shows that the water content decreases gradually with increase in the binder content. The estimated value is plotted with λ of 0.25 and β of 0 which coincide with the measured value very well. (Kitazume & Terashi, 2013, 75.)

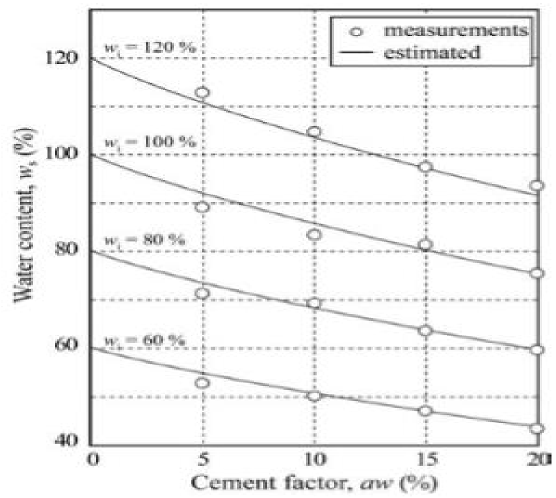


Figure 23. Change of water content by cement stabilization (Kitazume & Terashi, 2013)

4.4 Mechanical properties

4.4.1 Stress strain

An unconfined compression test was conducted on in-situ cement stabilized soil in Tokyo and presented as a graph of strain and stress curve as shown in Figure 24. The result clearly shows that the stabilized soil has very high strength stress-strain curve and small axial strain at failure whereas the original soil has small strength and larger axial strain failure. The original soil Tokyo Port clay w_L (Liquid limit) of 93.1% and w_p (plastic limit) of 35.8%) was stabilized with ordinary Portland cement with cement content, α of 112kg/m^3 (Kitazume & Terashi, 2013, 80.)

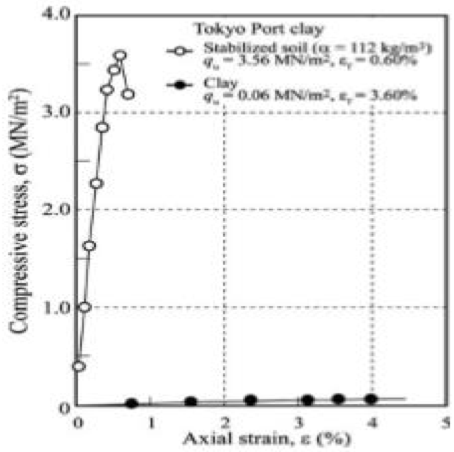


Figure 24. Stress strain of in-situ cement stabilized soil (Kitazume & Terashi, 2013)

4.4.2 Compressive strength

Since soilcrete is a composition of both soil and cement, the compressive strength of the materials lies between soil and cement. The typical value of strength of soil is 200 KPa, soilcrete is 2000KPa and cement is 20000Kpa. Compressive strength of soilcrete typically after 28 days ranges from 0.2 to 5 MPa. (Tadio, 2015.)

4.4.3 Tensile and bending strength

There are various ways to evaluate the tensile strength of stabilized soil. Split tension test, simple tension and bending test are commonly used for this purpose. In the split tension test, the disc of stabilized soil is loaded across the diameter and compressive load is applied until failure. In simple tension test, the cylindrical shaped stabilizes soil subject to direct tensile force. In the bending test, the load is applied to the rectangular shaped stabilized soil sample and the bending strength is calculated by tensile stress induced at the bottom surface of the sample.

According to Kitazume & Terashi (2013), in the experimental studies performed by Namikawa and Koseki, (2007) found tensile strength $б_{ts}$ increases almost linearly with the compressive strength q_u, irrespective with the amount, type and the initial water content in the soil.

The typical tensile strength of soilcrete is between 8 to 14% of its UCS.(D.A. Bruce and Bruce 2003.)

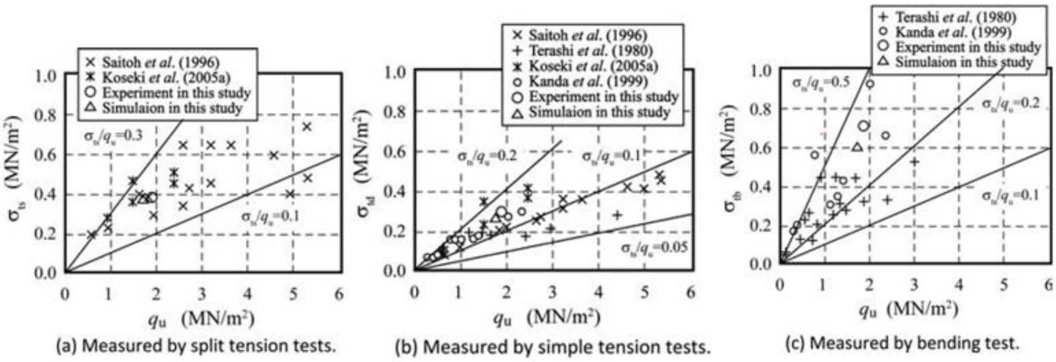


Figure 25. Tensile strength of laboratory stabilized soil (Kitazume & Terashi, 2013)

4.4.4 Long term strength

Jet grouting method has been used in various projects in many developed countries. Usually, in every project laboratory tests were performed to determine the strength over time. The verification tests are done at the actual construction site. However, the test data are mostly based on sample taken no more than few months old. Only a very limited number of researchers have studied the strength over time for years or decades.

The long-term strength of stabilized soil depends on two main aspects. The first one is the strength increase over time in the core part of the jet grouted column which has a negligible influence by the surroundings conditions. The second aspect is possible deterioration on the peripheral surrounding of the soilcrete column resulting in the decrease in strength over time. Figure 26 and 27 shows long term strength of stabilized soil. (Kitazume & Terashi, 2013.)

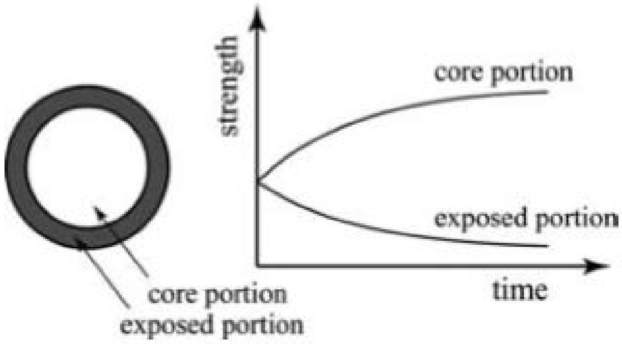


Figure 26. Long term strength of stabilized soil (Kitazume & Terashi, 2013, 98)

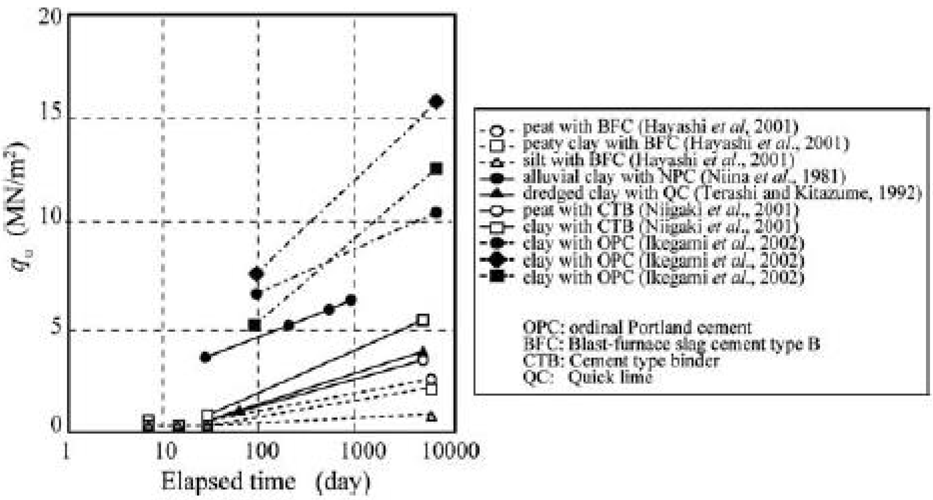
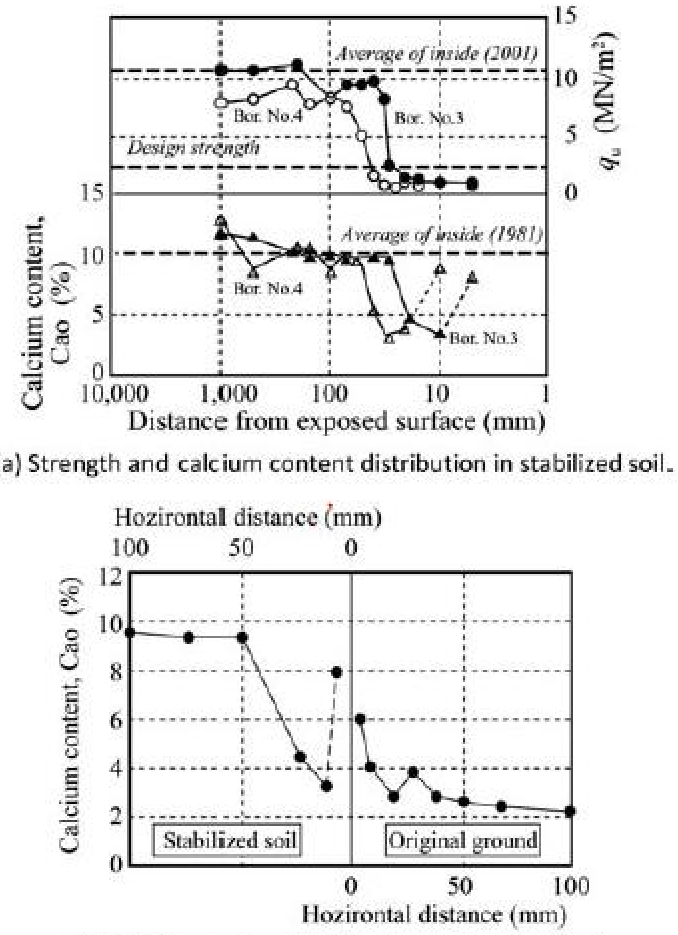


Figure 27. Relation between q_u and elapsed time in situ stabilized soil (Kitazume & Terashi, 2013, 100)

Various studies have concluded that the increase in strength of stabilized soil at core part increases linearly with the logarithm of elapsed time irrespective of amount of binder, soil type or laboratory / in situ stabilized soil.

On the other hand, laboratory mixed specimens are tested and studied under different exposure conditions such as direct contact with sea water, tap water and saturated clay. Furthermore, they are compared with the specimen wrapped with a sealant. The test results show that the deterioration starts first at the outer surface and progress inwards. The rate of deterioration process is slow and depends on the exposure conditions. Another reason for the strength decrease may be the leaching ca2+ ions from the stabilized soil column. Figure 28 shows the calcium leaching from the stabilized soil to the unstabilized soil causing the deterioration at the periphery. (Kitazume & Terashi, 2013, 99.)



(a) Strength and calcium content distribution in stabilized soil.

(b) Calcium content distribution in stabilized soil.

Figure 28. Long term strength and calcium content in stabilized soil (Kitazume & Terashi, 2013)

4.4.5 Modulus of elasticity (Youngs modulus)

An elastic parameter of soil used in estimation of settlement due to the static loads is called modulus of elasticity. Modulus of elasticity, E50 is defined by the secant modulus of elasticity in a stress- strain curve at half of the unconfined compressive strength, q_u. The modulus of elasticity of soilcrete is 350 to 1000 times qu for laboratory samples and 150 to 500 times qu for field samples. According to Tadio, 2015, the relation of E50 (Elastic modulas at 50% from the maximum load) and UCS various from 50 to 300 times for sample with UCS less than 2 MPa and 300 to 1000 times UCS for sample with UCS more than 2 Mpa.

In the study (Niina et al., 1981) of laboratory cement stabilized soil (16 clays and sandy silts with Portland cement 10% ,20% and 30%), the E50 almost linearly increase with q_u as shown in Figure 29. In similar study (Kitazume & Terashi, 2013) of laboratory lime stabilized soil the E_{50} exponentially increase with and unconfined compressive test, q_u.

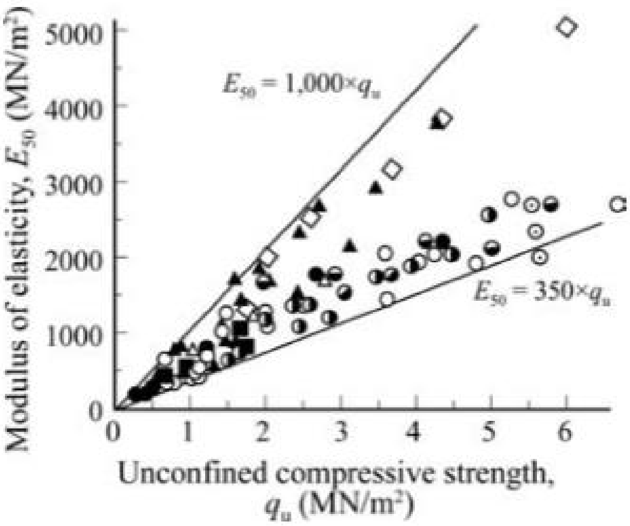


Figure 29. Modulus of elasticity, E50 of cement stabilized soil (Kitazume & Terashi, 2013)

4.4.6 Poisson's ratio

The Poisson's ratio is calculated by measuring axial and volumetric strains. The Poisson´s ratio, μ of in-situ stabilized soil can be given as equation below. In the study stabilized soil of in-situ, the poisson's ratio compared to unconfined compressive test range between 0.28 to 0.45, irrespective of compressive strength. The study carried out in laboratory stabilized soil, sand, silt, loam and organic soil by Building centre of Japan shows the frequency of Poisson's ratio from 0.19 to 0.30 and the average of 0.26. The Poisson's ratio was almost same for the laboratory and in-situ stabilized soil and not much depends on type of soil, strength of soil and soil size. (Kitazume & Terashi, 2013, 86.)

$$\mu = \frac{\varepsilon_f - \varepsilon_{vf}}{2\varepsilon_f} \quad (6)$$

Where,

μ : poisson's ratio

ε_f: axial strain at failure (%)

ε_{vf}: volumetric strain at failure (%)

4.5 Influencing factors

The hydration reaction between the binder and the soil is the basic mechanism of the strength increase in soilcrete, where the most commonly used binders are lime and cement. The strength increase of such soilcrete depends on many influencing factors which are divided into four sub sections shown below in Table 11.(Terashi et al.,1997). The Figure 30 below explains the cement hydration process starting with the reduction of water content followed by an improvement in physical properties and hydration reactions over the time. Although, the rate of strength increase differs in both reactions the cations exchanging quality of both binder lead to the improvement in the plasticity of soil. The pozzolanic reaction with cement stabilized soil is rapid and the hydration complete within several weeks. However, in the studies conducted by Nikbakhtan & Osanloo, (2009), while comparing the physical and mechanical property of soilcrete before and after jet grouting it was found that the water content had rose significantly after jet grouting from 38% to 50 -75%. The cement hydration mechanism was discussed in section 3.5.

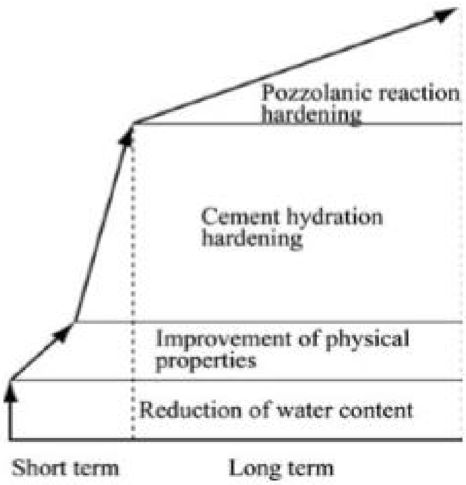


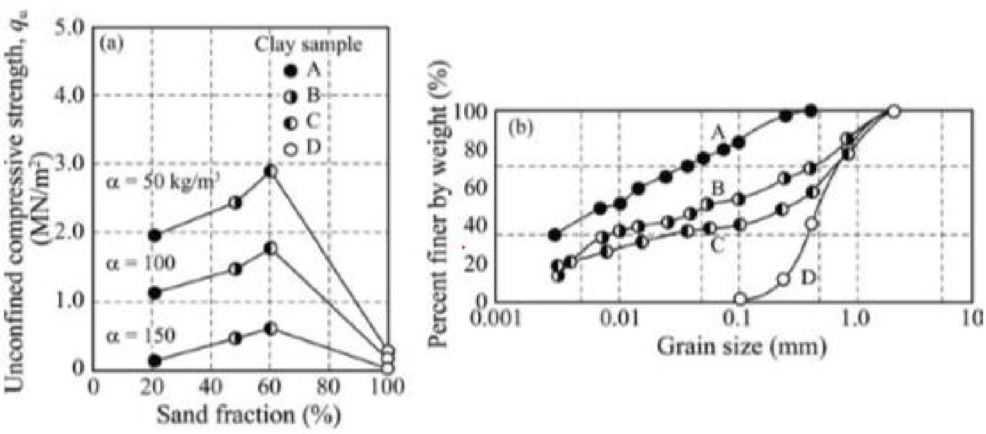
Figure 30. Mechanism of cement stabilization (Kitazume & Terashi, 2013)

Table 11. factors affecting increase in strength

I.	Characteristics of binder	1. Type of binder 2 . Quality 3. Mixing water and additives
II.	Characteristics and conditions of soil (especially important for clays)	1. Physical, chemical and mineralogical properties of soil 2. Organic content 3. potential Hydrogen (*pH*) of pore water 4. Water content
III.	Mixing conditions	1. Degree of mixing 2. Timing of mixing/re-mixing 3. Quantity of binder
IV.	Curing conditions	1. Temperature 2. Curing period 3. Humidity 4. Wetting and drying/freezing and thawing, *etc.* 5. Overburden pressure

4.5.1 Types of soil

Erodibility of soil depends on the type of the soil. Cohesionless soil such as gravely soil, clean sands, cobbly soil are easy to erode whereas high plasticity silts and clays are most difficult to erode (HBI 2005). High energy input was required for the grouting in medium and very stiff silty clay. (Poh & Wong, 2000). According to Kitazume & Terashi, (2013), Niina et.al., (1981) defines the strength of specific type of soil stabilized with cement depends on the grain size, binder amount, water content, pH value and organic content. The study carried in total 21 different soil types were stabilized with Portland cement with binder factor aw 20% and the influence of soil type on unconfined compressive strength q_u shows the humic acid content and pH of original soil are the most dominant factors influencing the strength. In another study two artificial soil B and C were prepared and mixed with natural soil named A alluvial clay (w_L 62.6% and w_p of 24.1%) and sand D. Portland cement was used to stabilize soil of three magnitude of α and tests were carried out in 28 days of curing. The unconfined compressive strength, q_u in this study depends upon the sand fraction, irrespective of the amount of cement. The highest improvement achievable can be 60% of sand fraction as shown in figure 31. Figure 32 shows different soil erodibility characteristics.



(a) Sand fraction of soils. (b) Grain size distributions.

Figure 31. Influence of grain size distribution in cement stabilization. (Kitazume & Terashi, 2013)

Figure 32. Different soil erodibility characteristics property (Schaefer, 1997, HBI 2004)

4.5.2 Nozzle, rotation and lifting speed

The quality of the soilcrete is affected by the shape, dimension and accuracy of the nozzle. According to Shibazaki (2003), a nozzle with a narrowing angle of 13 degrees and a straight portion of 2.5 to 3 times the diameter is recommended for jet grouting applications. Nozzles should accurately be finished from inside, outside, and the exit point in order to create a focused jet to erode the soil.

A study conducted by Yoshida et al. (1991) to find the effect of the number of nozzles (Np) and rotational speed (Rs) on cutting distance using a silty sand soil with NSPT 3 to 6 blows per 300 millimeters. The cutting distance increases with the number of jet nozzles and decreases when the jet rotational speed increases for a given jetting energy. The increasing the rate of cutting distance diminishes after 10 passes, which shows it is the optimum number of nozzles. The authors emphasized that to have the minimum number of passes (Np) within a given lifting step (Δz), the withdrawal rate (vt) has to be selected in such a way that the duration of jetting (Δt) is matched with the rotational speed (Rs), i.e., Δt = Np/Rs = Δz/vt. In lifting step of Δz, the time Δt for cutting the soil can be calculated by Δt = Δz/vt, where vt is the withdrawal rate of the monitor. (Ho, 2005).

The experimental study done in cohesive soil, non-cohesive soil and low cohesion soil shows that the soilcrete diameter increases with the increase of the rod-lifting time. In addition, when the rotational rate of a speed increases, the diameter of the soilcrete also increases. However, after the optimal speed, the diameter decreases when the rotational rate increases as seen in Figure 33 and 34 below. (Malinin et al., 2010.)

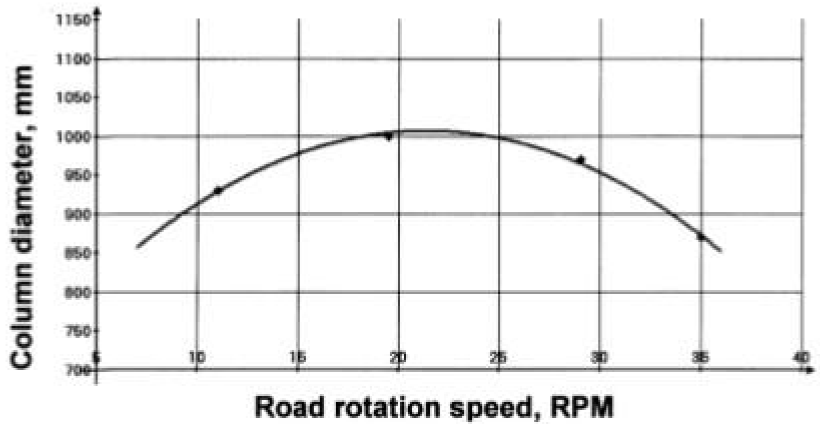


Figure 33. Relationship between soilcrete diameter and rotational speed. (Malinin, 2010)

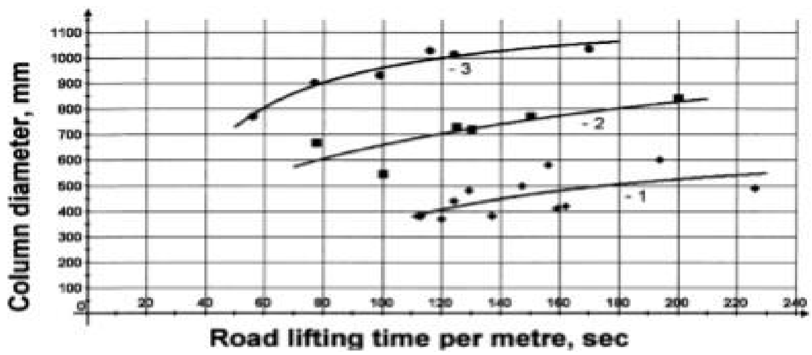


Figure 34. Relationship between soilcrete diameter and lifting rate. 1) cohesive soil, 2) soil with low cohesion, 3) non-cohesive soil. (Malinin, 2010)

4.5.3 Jetting pressure and flow rate

The diameter of soilcrete is directly dependent on the parameter of speed of the nozzle, withdrawn rate and the eroding time of the soil (Brill et.al., 2003). According to Mussger et.al., 1987, the pressure of jetting of 60 MPa can increase the soilcrete diameter. To erode the soil, jetting energy must be greater than the compressive strength of the soil. If the jetting pressure is lower than the compressive strength the prolonged time of jetting can still erode the soil to a certain limit. It is also possible to erode the soil with the lower pressure with a longer exposure time. The increase in water pressure increases the eroding distance after the pressure exceeds the ultimate compressive strength of the soil as shown in Figure 35 below.

According to Tinoco 2012, air shroud around the water jet increases the eroding distance among water jet in air, water, and water with shrouded air. The factor influencing the cutting distance efficiency of jet grouting in different soil types eroded by water jet triple fluid and grout jet in single fluid, triple jet system was found to be more effective in cutting sand, silt and soft rock as explained in Figure 36 below. (Yahiro & Youshida, 1973.)

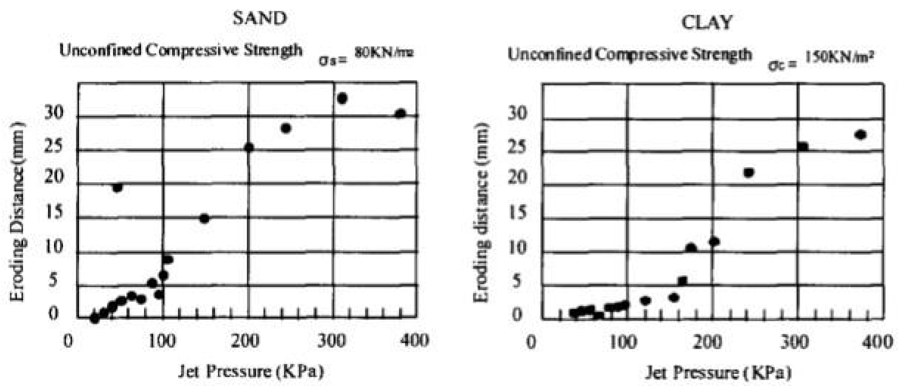


Figure 35. Relation between eroding distance and jet pressure (Essler & Yoshida, 2004)

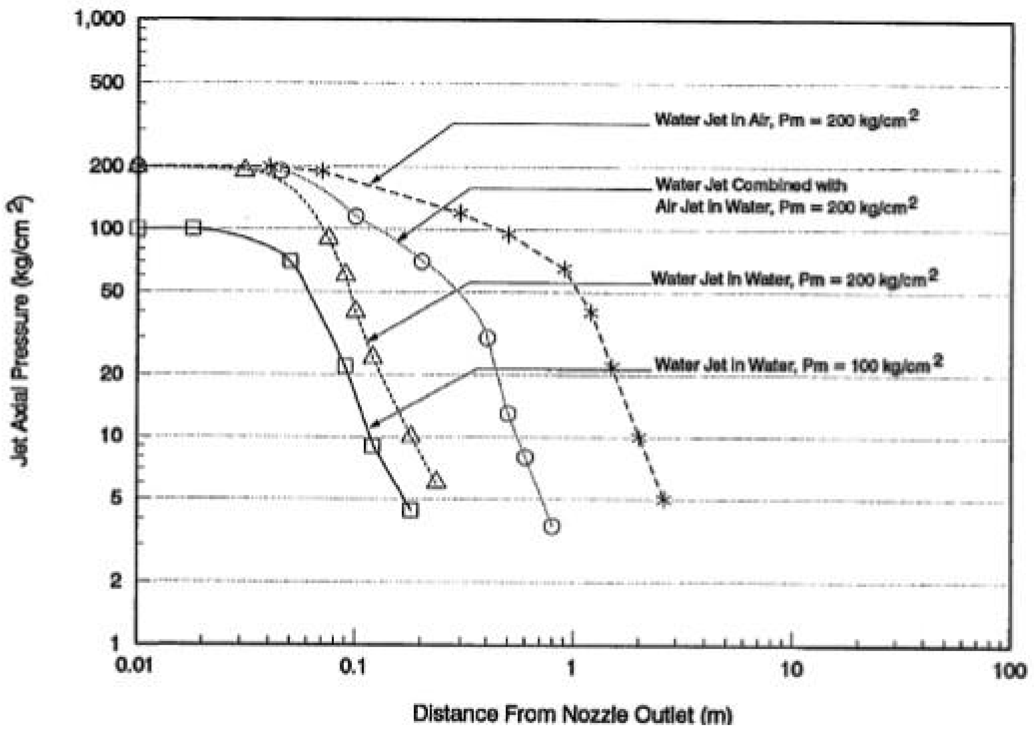


Figure 36. Jet axial pressure of water jet versus cutting distance from nozzle outlet adopted from (Nikbakhtan, 2015)

4.6 Empirical relationship to calculation Soilcrete diameter

There are many operating parameters and influencing factors in jet grouting execution making it extremely difficult to derive an empirical relation between soilcrete diameter and operating parameters accurately. Most of the empirical formulas are derived from the practical case studies comparing the diameter achieved and different parameters used. These sets of data predict the diameter of soilcrete under similar soil conditions. Although it does not always guarantee to achieve the same results from a similar case. Many authors have derived various empirical formula to calculate the diameter of the soilcrete and many of them have limitations in the parameters. The computer-based programmes help in predicting the diameter with the fed data which has certain boundary conditions and reliability depends on the accuracy of the input in the system. Some of the empirical relations are discussed blow.

According to Essler (1995), the diameter of the soilcrete can be derived from the relation of input jetting energy and the ability of soil to be eroded as shown in Figure 37.

$$E = 7.85 \times L \times D^2 \qquad (7)$$

E: Volume of cut per minute (Litre)
L: Lift speed (cm/min)
D: Soilcrete diameter (m)

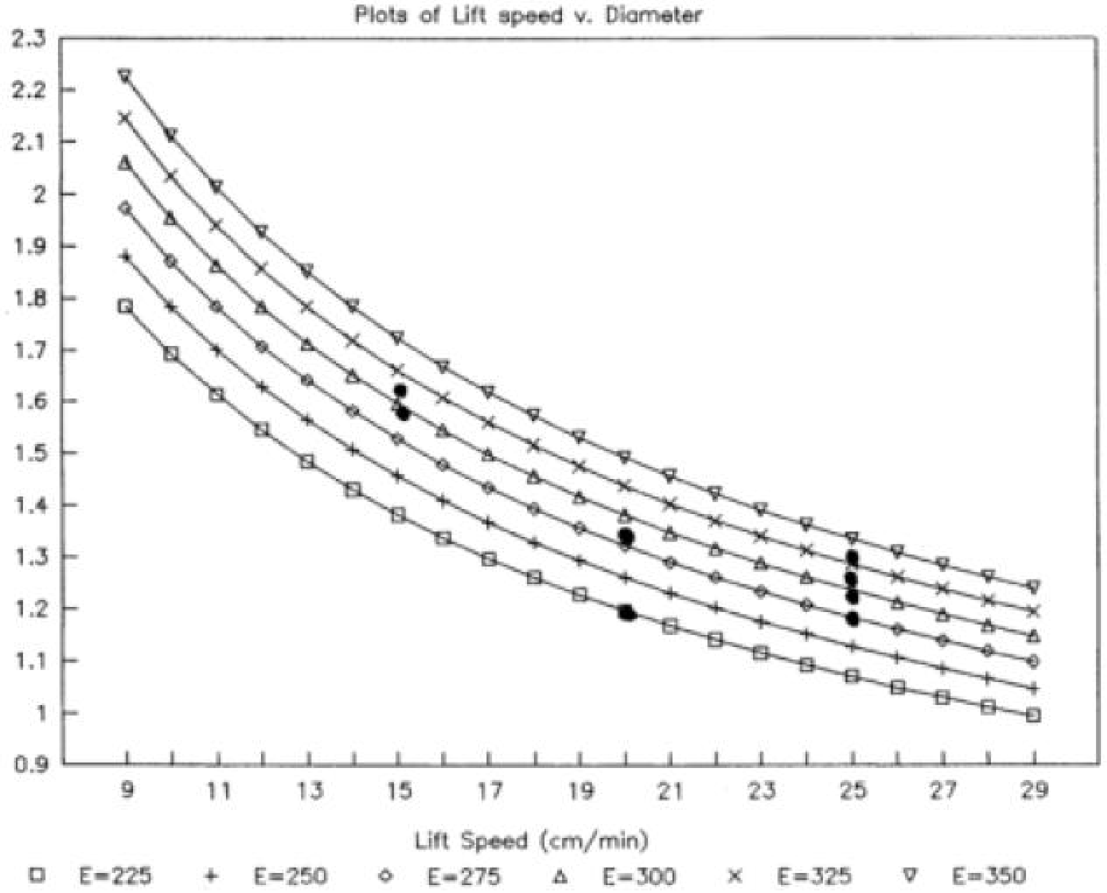


Figure 37. Plots of diameter vs lift speed for different values of E (Liter/min). (Essler 1995).

Mehalis et al. (2004) derived a similar relationship between specific jet grout energy and soilcrete diameter. It was concluded the specific jet energy range can be used for the successful execution of different jet grout systems. For single jet system specific energy of 17 MJ/m and 30MJ/m can be used. Similarly, for double fluid system 40 MJ/m and 80 MJ/m specific energy can be used whereas specific energy not exceeding 130 MJ/m used in triple fluid system.

$$E_S = 0.0101 \times DD^{2.02} \quad (8)$$

During the jet grouting process, the mixture of grout, water and soil comes to the surface through the space between bore hole and the drilling rod, which is called spoil. The spoil contains the same composition of the mixture that can be used in estimating the column diameter. Kimpitris et.al., (2013); Lesnik, M (2003) formulated a theoretical model to determine the diameter of cylindrical jet grouted elements which is based on mass balanced correlation of the inflow during the jet grout process, eroded mass and the spoil return.

$$\mathrm{D} = \sqrt{\frac{Q_v \cdot (\rho_V - \rho_r)}{\frac{\pi}{4} \cdot V_Z \cdot (\rho_{DS} - \rho_B)}} \quad (9)$$

Where,
D: diameter of jet grout element(meter)
Q_v: grout flow rate that is pumped into the soil (lit/min)
ρ_V: specific weight of the grout (g/cm^3)
ρ_r: specific weight of the spoil material (g/cm^3)
V_Z: lifting speed of the lifting rod (m/min)
ρ_{DS}: specific weight of the jet grout element (g/cm^3)
ρ_B: specific weight of the water saturated soil (g/cm^3)

In another study conducted by Nikbakhtan & Ahangari (2010), the empirical relationship between the diameter and the rotation speed, grout pressure and withdrawn rate were studied. It was found that the diameter increases with increase in w/c ratio and grout pressure whereas diameter decreases with the increase of rotation and withdrawn speed. w/c ratio is more responsive to diameter than other parameters. Figure 38 shows relationship of diameter with w/c ration, grout pressure and withdrawn speed.

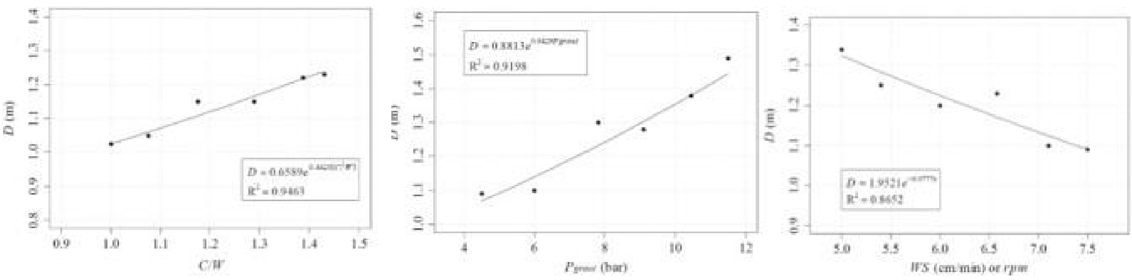


Figure 38. Relation of w/c ratio, grout pressure and withdrawn speed with diameter (Nikbakhtan and Ahangari 2010)

4.2.7 Calculation of soilcrete strength

Usually the soilcrete strength is evaluated with unconfined compressive strength (UCS). Unconfined compressive strength is the maximum axial compression that the material can withstand under the unconfined state. Some of the expected soilcrete UCS from various publications are summarized below in Table 12.

Table 12. UCS of soilcrete adopted from (Nikbakhtan, 2015)

Author/Data	$\frac{w}{c}$	Soil Type - UCS (MPa)				
		Organic clay	Clay	Silt	Sand	Gravel
Welsh and Burke (1991)	-	-	1 to 5	1 to 5	5 to 11	5 to 11
Baumann (1984)	1:1.5	-	-	6 to 10	10 to 14	12 to 18
	1:1.0	-	-	3 to 5	5 to 7	6 to 10
Paviani (1989)	-	-	1 to 5	1 to 5	8 to 10	20 to 40
Teixeira et al. (1987)	-	0.5 to 2.5	1.5 to 3.5	2 to 4.5	2.5 to 8	-
JJGA (1995)	-	0.3	1	1 to 3	-	-
Guatteri et al. (1994)	-	-	0.5 to 4	1.5 to 5	3 to 8	-
(Bell 1993)	-	-	0.5 to 8	4 to 18	5 to >25	5 to >30
(Miki 1985)	-	-	<5	5 to 10		
(M. Shibazaki 1991)	-	-	10	30		
(B Nikbakhtan and Osanloo 2009)		-	2.4		-	-
(B. Nikbakhtan and Ahangari 2010)	-	-	0.9 to 3.3		-	-

Nikbakhtan and Ahangari (2010) conducted study on jet grouted column in fine grained clayey soil to find the relationship between soilcrete UCS and its diameter with w/c ratio, grout pressure and rotation and withdraws speed. The laboratory UCS test concludes the UCS increases with the increase in w/c ratio and grout pressure whereas UCS decrease with the increase in rotational and withdrawn speed which can be seen in Figure 39. The authors also concluded that the UCS of soilcrete is more responsive to w/c ratio than other parameters

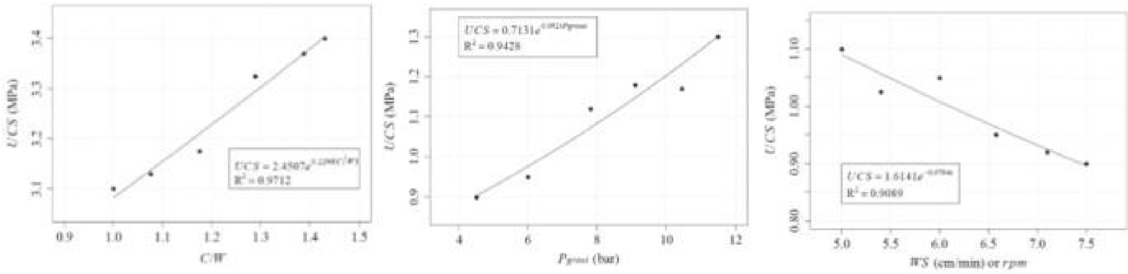


Figure 39. Relation of w/c ratio, grout pressure and withdrawn speed with UCS (B. Nikbakhtan and Ahangari 2010)

Some empirical formulas proposed by various authors are given below.

$qu = qu(t_0) + K\log t/t_0$ (10)

Increase in cement content increases the Unconfine Compressive strength of soil. (Mitchell J.K et al., 1974)

Where,

$qu(t_0)$: Unconfine Compressive Strength at t_0 days, KPa

K: 480 A_w for granular soil 70A_w for grain soil

A_w: Cement content percent by mass

t: Curing time

Shear strength of Soilcrete can be calculated using following equation (S. Satio et al.,1980)

$\tau_0 = 0.53+0.37(UCS) - 0.0014(UCS)^2$, $(UCS \leq 60 kg/cm^2)$ (11)

where,

τ_0: 28-days shear strength (kg/cm^2) obtained by direct shear test with zero normal stress

UCS: 28-days unconfine compressive strength (kg/cm^2)

Another equation was suggested by Narendra et al, (2006) specially to calculate strength off soilcrete in laboratory.

$UCS = \frac{A}{B^{\frac{wC}{C}}}$ (12)

Where,
A: a coefficient related to the type of clay, liquidity index and age of the mixture
$\frac{wC}{C}$: the soil-water/cement ratio
B: an empirical constant which is independent of the type of clay (1.22 to 1.24)
Calculation of strength of soilcrete in cohesive soil for the specific type of cement is proposed as equation by F.H. Lee et al. (2005)

$$UCS = UCS_0 \; X \frac{e^{mx(\frac{S}{C})}}{(\frac{W}{C})^n} \qquad (13)$$

Where,
S/C: soil cement ratio
W/C: water cement ratio
UCS_0, m and n are experimental constants

5 PRACTICE IN FINLAND

Jet grouting has been used for the underpinning work in many cases in Finland. Foundation restoration and excavations near buildings and structures are among the jet grouting projects cases in Finland. The Jet grouting technique is getting popular for being a direct method, rapid execution providing permanent strong bonds for the soil compared to other methods. There are many alternatives for excavation pit support, like sheet piling, RD-pile wall, combination wall, which can be anchored (permanent or temporary) or without anchors. The correct method ought to be chosen case-by-case; whenever existing structures are close by, Soilcrete is a reasonable alternative to consider. Keller used single fluid system in the 1970s and started double fluid system jetting in the 1990s. The double fluid system with its variations is used in Finland. Double fluid system has been effective and used for soilcrete construction under the groundwater level. Triple fluid system has rarely been used in Finland. Although very few construction companies in Finland provide jet grouting solutions, KFS Finland Oy is the major operator and the market leader in at the present time which provides engineering design and quality execution of jet grouting in Finland. Figure 40 below shows a typical jet grouting process of a project. (Virolainen, interviewed 20.06.2019.)

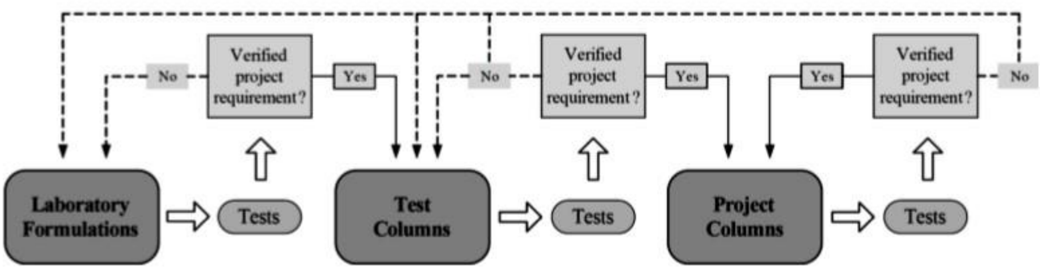


Figure 40. A typical jet grouting project process (Tinoco, 2012)

5.1 Design

Design of Jet grouting starts with the soil test report grain size distribution chart (GSD) which provides the detail data of types of soil layers, shear strength parameters i.e. cohesion and frictional angle, water content, unit weight and ground water level. Structural loads are calculated, and the data are fed into the GGU software (geotechnical analysis computer software). A screenshot picture of GGU software is shown below in Figure 41. This software has a huge set of capabilities in analysing data. For example, bearing capacity safety and settlement analysis to DIN 4017 and 4019, inner stability analysis to DIN 4093, active and passive earth pressure, water pressure, moment and shear force, normal force etc. The safety factor of 4 according to Eurocode is used in designing of jet grouting column. Although some FEM (Finite element method) analysis are quite common, BIM (building information modelling) has rarely been used for the jet grouting projects in Finland. Implementation of BIM is expected in near future projects. (Virolainen, interviewed 20.06.2019.)

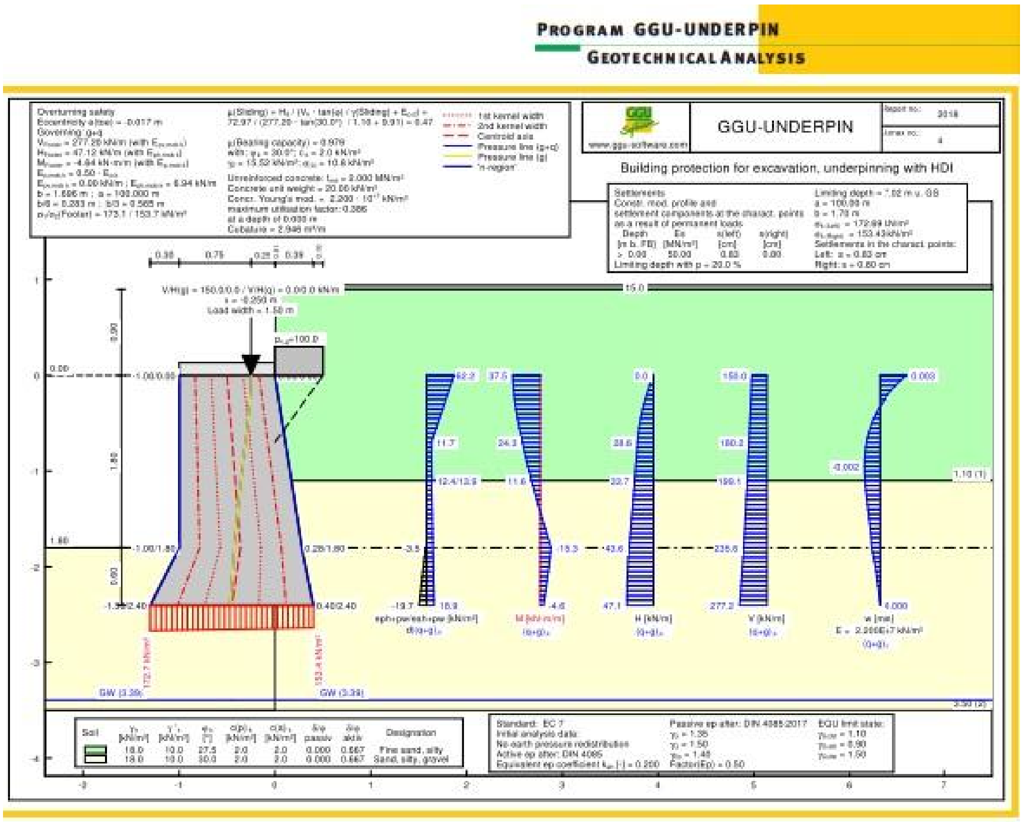


Figure 41. Geotechnical analysis of jet grouting underpinning (GGU software, 2019)

5.2 Working Methods

Setting up of the jet grouting station is very convenient since KFS Finland has its own equipment. Sometimes internal renting of equipment is also possible in bigger projects. Currently, experienced workforce in jet grouting site works are limited in Finland. Therefore, during the time when projects need extra experienced employee, internal help within Keller can be sought. Usually, setting up station usually takes a couple of days. The completion of the project time depends on the types of the project and alternatives used. (Virolainen, interviewed 20.06.2019.)

5.3 Quality Control

Since jet grouting construction is not visibly possible to control like in other construction, it needs a great deal of planning, monitoring in every stage of execution to achieve the desired outcome. Quality controls involve testing of the materials used, documenting work which has been carried out, for example, design updates, drilling documents, real execution drawings showing all the technical details, date and time of the execution. The final part of quality control process provides the test and reports obtained from soilcrete samples. Drilling documents provide all the parameters of jet grouting execution which are very important documents in this quality control documentation process.

5.3.1 Execution documents

The documents that are needed prior to the main jet grouting works

- Geotechnical report of sub soil report
- Technical specifications
- Method statements
- Technical specifications of jet grouting plant
- Description and characteristic of materials
- Preliminary test report
- Execution drawing – Soil profile
- Shape of the soil elements
- the number of elements and clear reference for each
- Location and orientation of each element, tolerance and position
- Locations of possible underground obstructions, service and drainage
- The execution sequence (BS EN12716,2001; Page 24/25)

Figure 42 and 43 below show execution drawing of sheet pile tightening work.

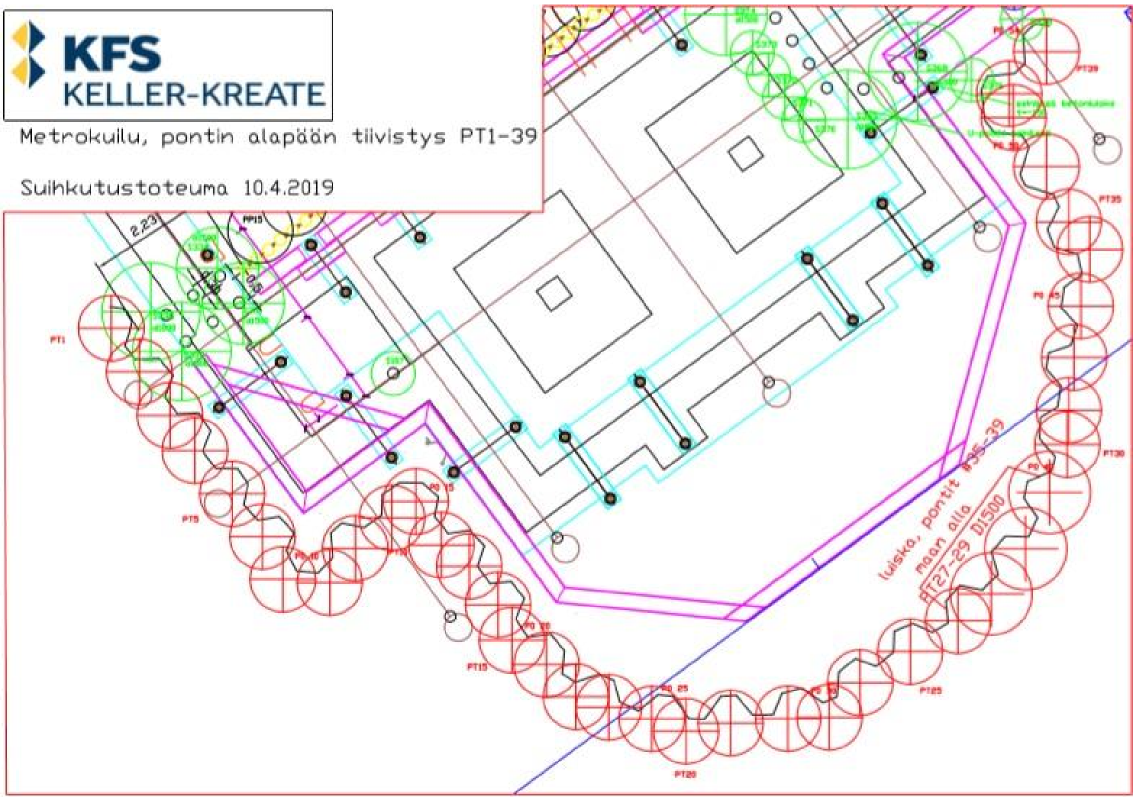


Figure 42. Execution drawing for sheet pile tightening works (Virolainen, 2019)

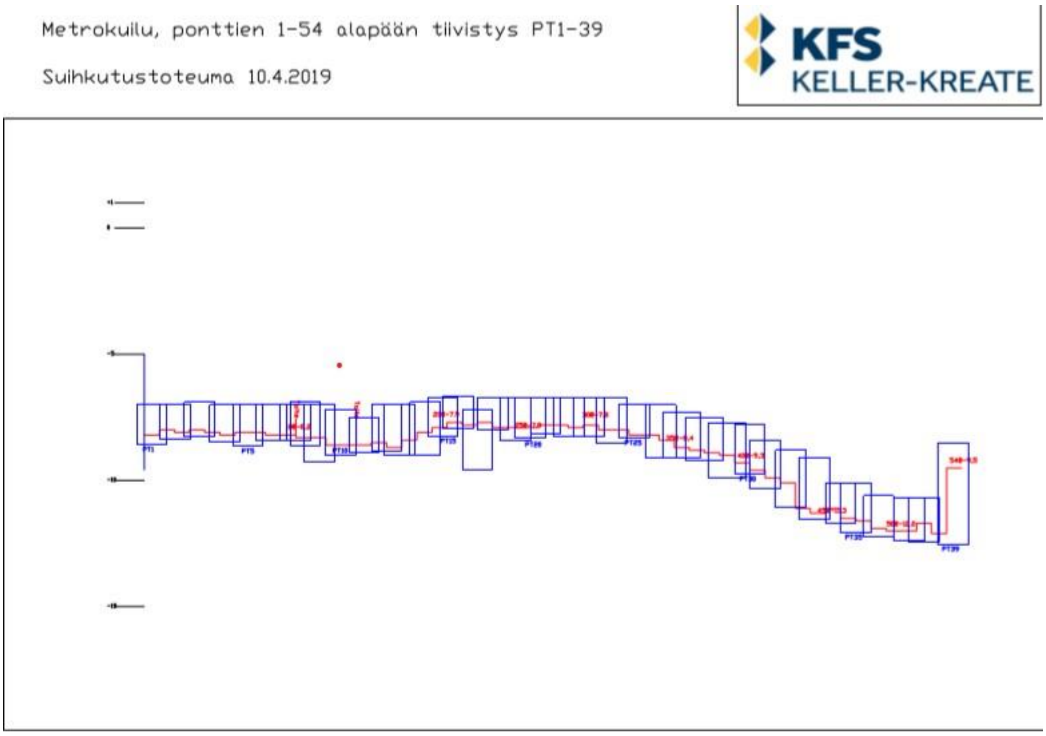
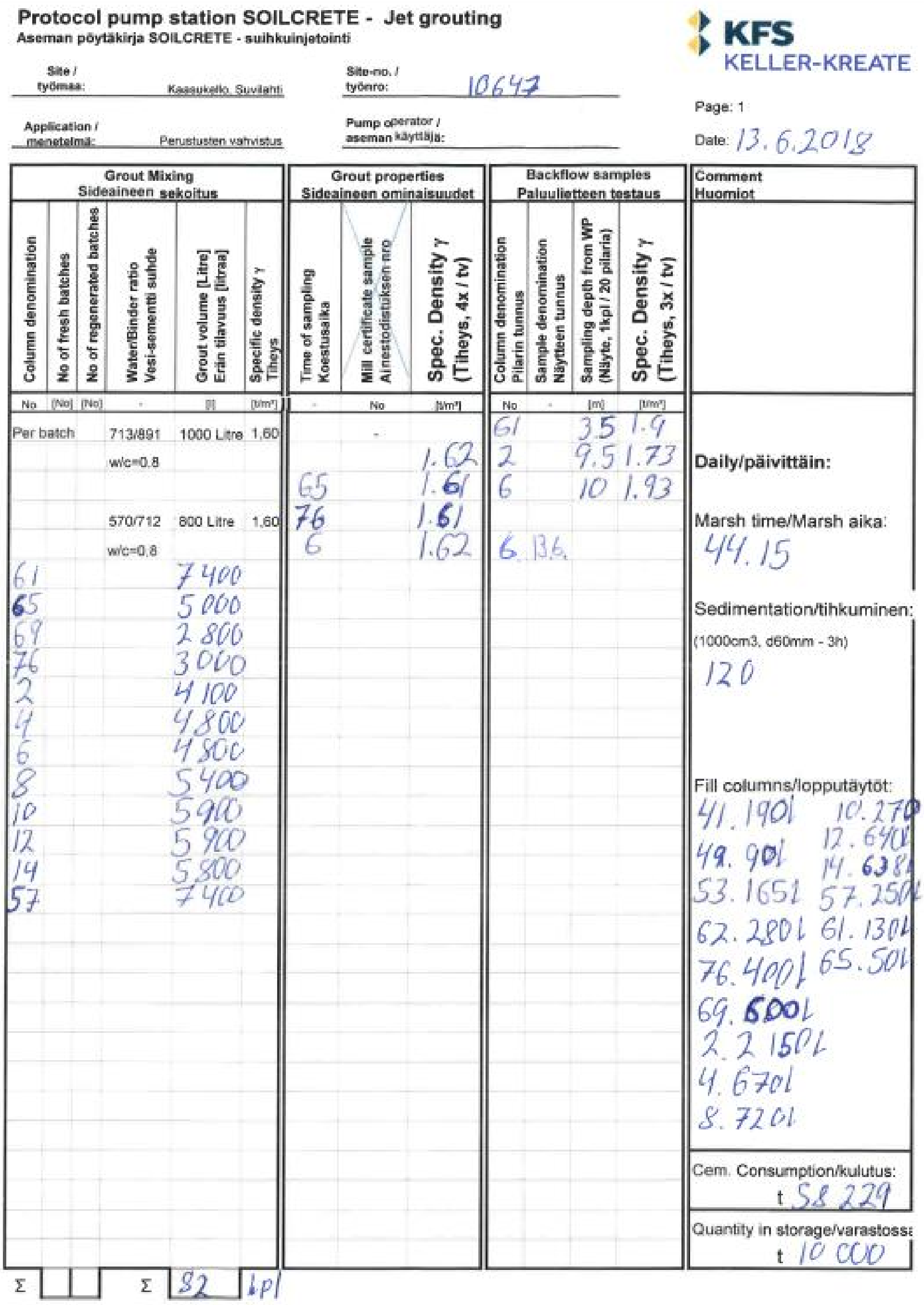


Figure 43. Execution drawing for sheet pile tightening works (Virolainen, 2019)

5.3.2 Pump protocols

The daily reports on the site execution of jet grout column includes drilling documents. Pump protocols are produced on site which specify the jet grouting parameters, date and time of execution, comments on spoil return and unexpected features. EN 12726 provides guidelines in annex D for the site record of jet grout work. Figure 44 shows the sample executed jet grout soilcrete pump protocol report.



Protocol pump station SOILCRETE - Jet grouting
Aseman pöytäkirja SOILCRETE - suihkuinjetointi

KFS KELLER-KREATE

Site / työmaa: Kaasukello, Suvilahti — Site-no. / työnro: 10647 — Page: 1
Application / menetelmä: Perustusten vahvistus — Pump operator / aseman käyttäjä: — Date: 13.6.2018

Grout Mixing / Sideaineen sekoitus						Grout properties / Sideaineen ominaisuudet			Backflow samples / Paluulietteen testaus				Comment / Huomiot
Column denomination	No of fresh batches	No of regenerated batches	Water/Binder ratio / Vesi-sementti suhde	Grout volume [Litre] / Erän tilavuus [litraa]	Specific density γ / Tiheys	Time of sampling / Koestusaika	Mill certificate sample / Ainestodistuksen nro	Spec. Density γ (Tiheys, 4x / tv)	Column denomination / Pilarin tunnus	Sample denomination / Näytteen tunnus	Sampling depth from WP (Näyte, 1kpl / 20 pilaria)	Spec. Density γ (Tiheys, 3x / tv)	
No	[No]	[No]	-	[l]	[t/m³]	-	No	[t/m³]	No	-	[m]	[t/m³]	
Per batch			713/891	1000 Litre	1,60		-		61		3.5	1.9	
			w/c=0.8					1.62	2		9.5	1.73	Daily/päivittäin:
						65		1.61	6		10	1.93	
			570/712	800 Litre	1,60	76		1.61					Marsh time/Marsh aika:
			w/c=0,8			6		1.62	6	13.6.			44.15
61				7400									
65				5000									Sedimentation/tihkuminen:
69				2800									(1000cm3, d60mm - 3h)
76				3000									120
2				4100									
4				4800									
6				4800									
8				5400									Fill columns/lopputäytöt:
10				5900									41.190l 10.270l
12				5900									49.90l 12.640l
14				5800									53.165l 14.638l
57				7400									62.280l 61.130l
													76.400l 65.50l
													69.600l
													2.2150l
													4.670l
													8.720l
													Cem. Consumption/kulutus: t 58 229
													Quantity in storage/varastossa t 10 000
Σ			Σ 82 kpl										

Figure 44. Protocol pump station soilcrete (Virolainen, 2019)

5.3.3 Strength test

According to Schaefer (2007), unconfined compression test, Triaxial test, Tension test, direct shear, spiriting tensile and CPT were the most common methods to verify the strength in soilcrete. These methods can be tested on core drilling, wet grabs and cast in place plastic pipe retrieve after curing samples. In addition to these methods, piezometer test, drilled and cast and cast in place piezometer sampling can be used to verify the permeability requirements. Similarly, FprEN 12716:2017E provides guidelines on expected sample quality class and methods of sampling. The methods of sampling in-situ are core drilling, fresh sampling liner, fresh sampling grabbing and spoil return whereas mixed in a laboratory are sample from laboratory. The quality of samples from core drilling are categorised in four classes depending on the quality tests which are given class A, B, C and D. For the laboratory sampling expected quality class is A, and for the rest of the Samples are A and B. For detail information on accepted quality to verify the material properties of soilcrete visit EN 12716:2017 E. Table 13 below shows the sampling and testing methods of soilcrete property quality control.

Table 13. Sampling and testing methods of soilcrete property quality control (Schaefer, 1997)

Requirement	Sample Method(s)	Test Methods
Strength	Wet grab (in-situ) cast in to molds Cast in place plastic pipe retrieved after cure Core drilling	Unconfined Compression Triaxial Tension Spiriting tensile strength Direct Shear CPT (in-situ) if soft enough
Permeability	As above plus: Cast-in-Place Piezometer Drilled and cast Piezometer	Permeameter Rising or Falling Head (in-situ) Packer Testing

5.3.4 Diameter checking methods

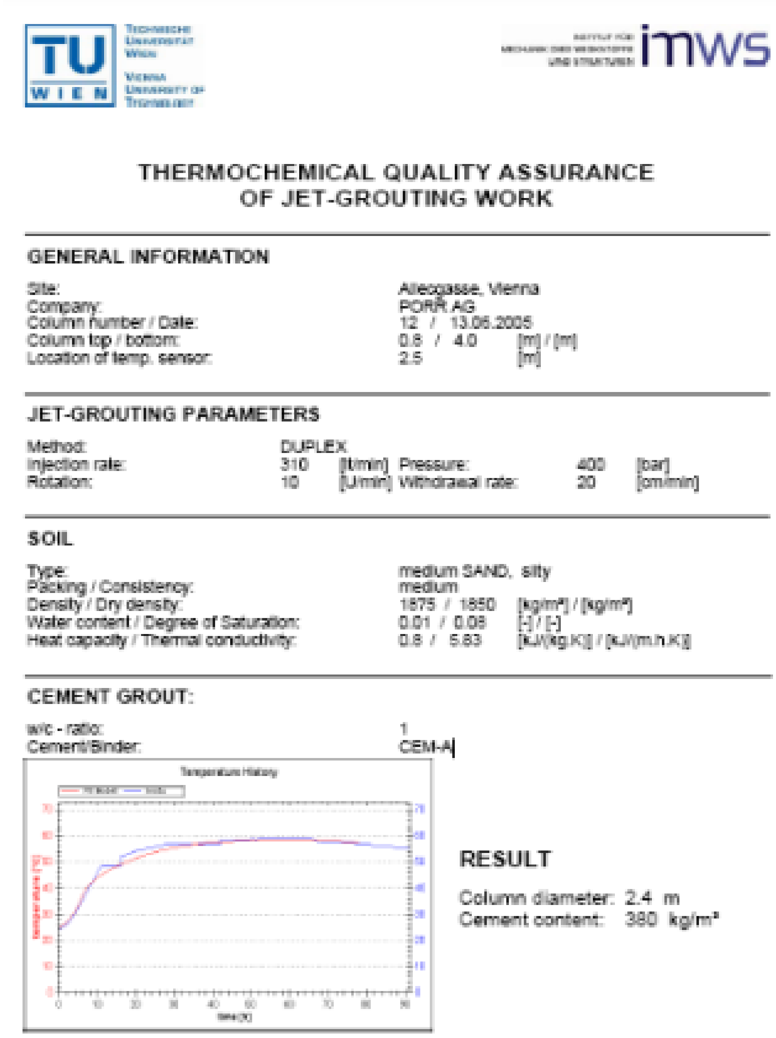
Visual Inspection – The most reliable method to determine the test column diameter is to excavate the column and measure the diameter and shape of the soil column on site. The test column concept is useful in setting the jet grouting parameters. But due to the surrounding structures, confined space and economic aspects, this may not be possible in many cases. The overlap columns or the column with other lateral connections are not safe to excavate. The surrounding soil types have a greater influence on the soil column strength, and its shape. Therefore, it needs to be taken into consideration before any excavation work. (Virolainen, interviewed 20.06.2019.)

Painted bars – Although painted bars are a simple and easy technique to determine the diameter of soil column, this method is not commonly used in Finland due to the reliability and production protocols. In this method, the bars are installed on the site with some difference in distance. For example, if column of diameter 1 meter has to be achieved, bars are kept from 40 cm, 50 cm and 60 cm from the centre of the column. After the grouting is complete bars are extracted and the erosion of the paint is checked. The hitting of the grout erodes the paint from the bar to the desired distance which proves that the grout hitting energy was enough to erode the soil to the desired distance. This technique is not suitable for soil column with an increased depth due to risk and the difficulty in extraction of these pipes. (Kimpritis, 2013; Virolainen, interviewed 20.06.2019.)

Thermal sensors- This technique is based on the temperature measurement by thermo chemical coupling. The thermo- chemical hydration process of cement in the centre of the jet grout column is measured right after the completion of jet grouted column. The measured temperature is recorded by the data collector which are then feed into the software to get in-situ curve. In-situ curves are Temperature curves related to time. This in-situ curve is then compared with the theoretical curve from Finite Element Method (FEM) analysis. The best fitting FEM curve with in-situ curve by means of software, then estimates the column diameter (D=2.4 m) and the amount of cement in jet grouted column 380kg/m^3 as shown in Figure 46. The input parameters for the software are temperature recorded, property of cement and thermal properties of surrounding soils.

Figure 45. Installation of temperature sensor (Meinhard et al., 2014)

Right after the completion of the jet grout column, a temperature sensor is installed through the high-pressure channel of drilled rod which was connected to the monitoring device. Figure 45 shows the installation of temperature sensor. The temperature sensor remains on place after the drilled rod is withdrawn.


THERMOCHEMICAL QUALITY ASSURANCE
OF JET-GROUTING WORK

GENERAL INFORMATION

Site:	Allegasse, Vienna
Company:	PORR AG
Column number / Date:	12 / 13.06.2005
Column top / bottom:	0.8 / 4.0 [m] / [m]
Location of temp. sensor:	2.5 [m]

JET-GROUTING PARAMETERS

Method:	DUPLEX				
Injection rate:	310	[lt/min]	Pressure:	400	[bar]
Rotation:	10	[U/min]	Withdrawal rate:	20	[cm/min]

SOIL

Type:	medium SAND, silty
Packing / Consistency:	medium
Density / Dry density:	1875 / 1850 [kg/m³] / [kg/m³]
Water content / Degree of Saturation:	0.01 / 0.08 [-] / [-]
Heat capacity / Thermal conductivity:	0.8 / 5.83 [kJ/(kg.K)] / [kJ/(m.h.K)]

CEMENT GROUT:

w/c - ratio:	1
Cement/Binder:	CEM-A

RESULT

Column diameter: 2.4 m
Cement content: 380 kg/m³

Figure 46. Construction site Vienna Result sheet for jet grout column (Meinhard et al., 2014.)

This technique is somewhat unclear because in-situ curve for the same single jet grout column suggests more than one diameter. Moreover, the recommendation is made to replaced Multi-phase hydration model developed for blended cement by Single phase cement hydration model. (Meinhard, et al., 2014). In addition, the properties of granular soil surroundings to determine the thermic conductivity are unclear. (Kimpritis, 2013.)

Acoustic Column Inspector (ACI)- Due to the variety of the soil layer it is difficult to achieve the uniformly built soil create column. To achieve the desired uniform column geometry, diameter parameters control is essential. In most cases when a column cannot be excavated due to the installation depth and confined space Acoustic column inspector is used. Acoustic column Inspector is a device used to monitor the production parameters during the jetting process. ACI is also reliable in determining the contact between jet grouted elements and sheet pile walls, bored piles or other lateral support systems.

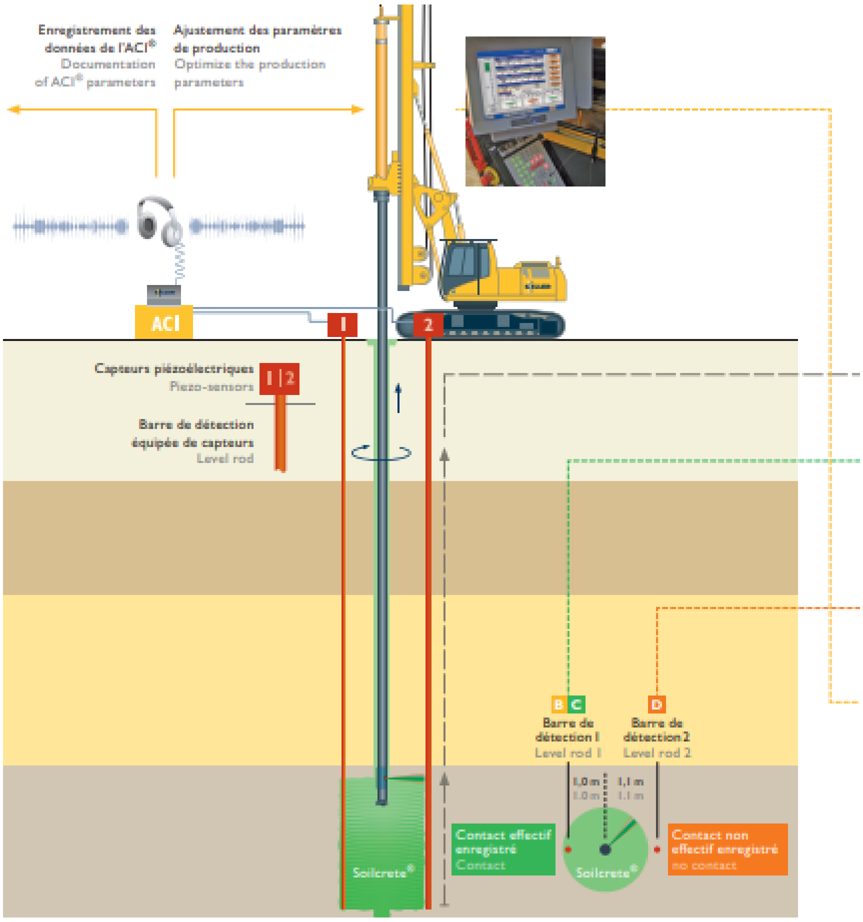


Figure 47. Acoustic Column Inspector setup (Keller, 2019. Brochure 67-04F/E)

The mechanism of this method is to connect the ACI device with the two rods which are kept some distance apart (as shown in Figure 47) to produces a specific sound signal to the recording device. During the grouting process when the grouting hits the rebars the produced sound intensity level determines if the desired column diameter is achieved. If the same sound intensity level has not been reached, the parameter must be changed to get the same sound intensity when grout hits the bars. In the Figure 48 mentioned below, level rod 1 is kept at a distance of 1 meter from the centre of soil column whereas level rod 2 is kept at 1.1 meter in distance from the centre of soil column. The data recording shows that there was no contact at level rod 2. (Virolainen, interviewed 20.06.2019.)

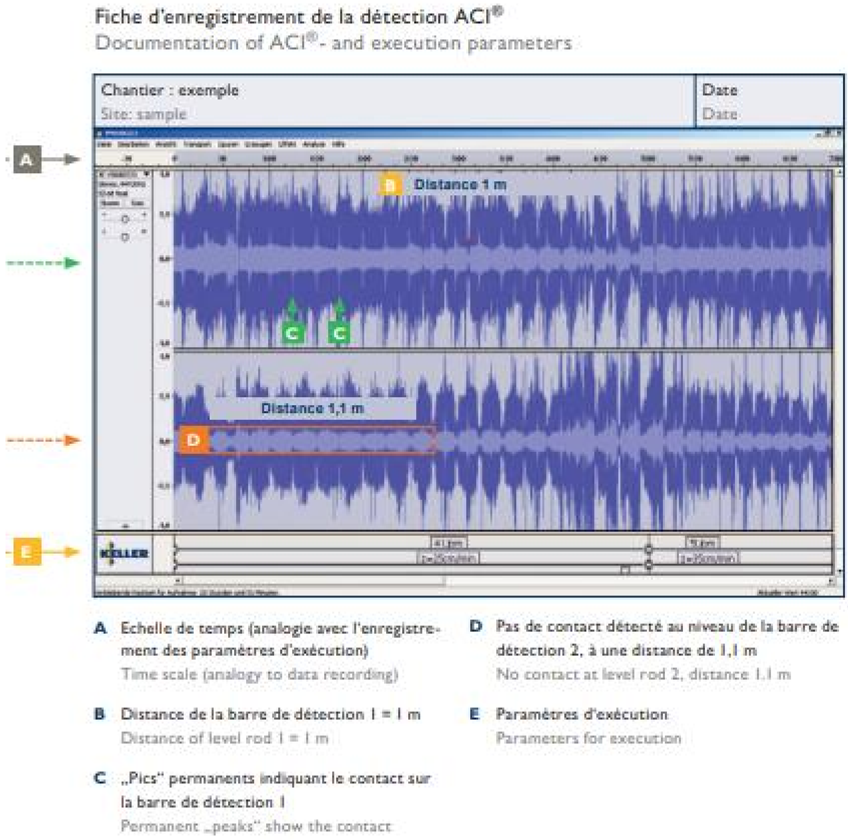


Figure 48. Documentation of ACI and execution parameters. (Keller, 2019. Brochure 67-04F/E)

5.4 Case studies

5.4.1 Introduction

At present time there are very few service providers for jet grouting solutions in Finland. Among them KFS Finland Oy is one of the active service providers. It is common in Finland to use jet grouting techniques with other alternatives like micropiles, sheet piles and anchoring depending on project needs. Here, jet ground techniques are extensively used as underpinning excavation support, sealing slab, ground water sealer and joint sealer between piles, sheet piles or other construction parts. Some of the jet grouted projects executed in Finland are listed in section 5.4.2.
Figure 49 is the preliminary structural design of a recent project on jet grouting wall under a building.

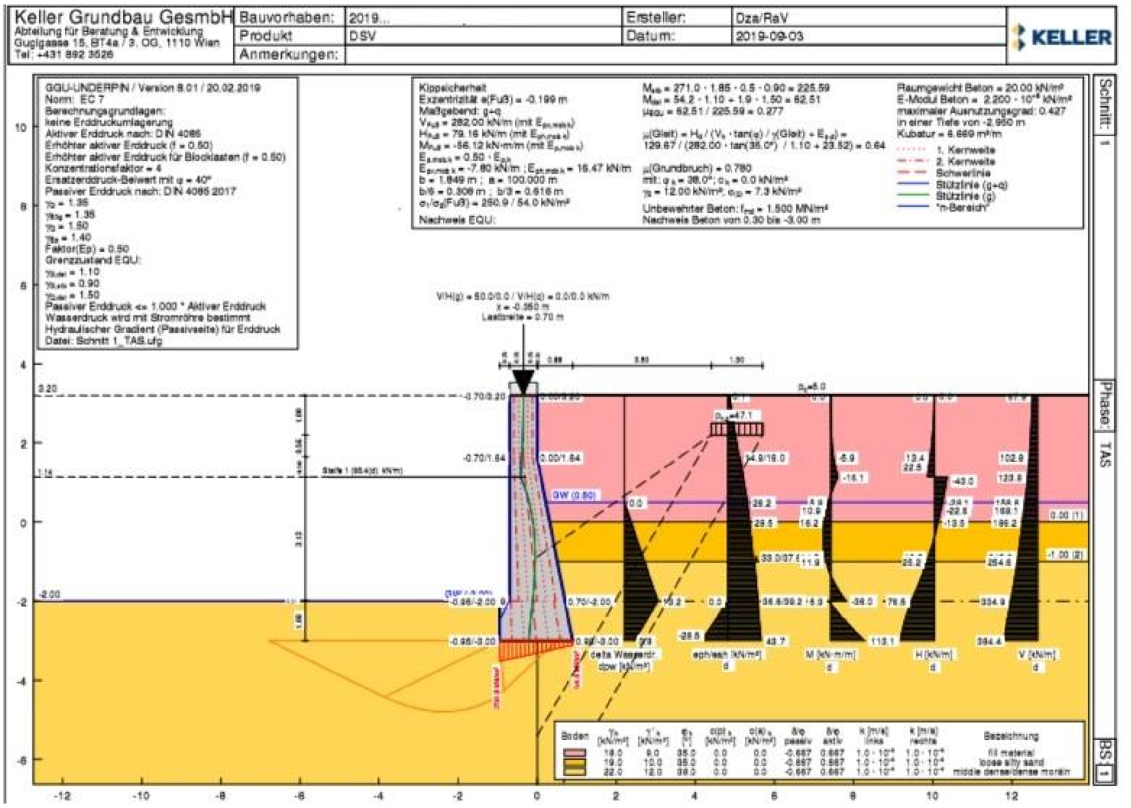


Figure 49. Jet grouting wall under the building (Virolainen, 2019)

5.4.2 Project

- Jet grouting project in Pohjoisranta 6, Helsinki

In the past wooden piles were used in the foundation of stone structures in many parts of Finland. After decades these wooden piles started to rot making the foundation weak. A similar block of flats which was built in 1819 in Helsinki, had sunk for decades due to decaying of the wooden piles in the foundation. The sinking of the foundation was 5mm per year. The project aim was to enforce the foundation by jet grouting and replacing the wooden piles with jet grouted piles. The work started with stone structure enforced with 122 jet grouted piles and after enforcing interior was restored, underground drain and floor were rebuilt, and surface was painted. (KFS Finland Oy, 2019.)

- Underpinning project in Kruunuvuori, Helsinki.

This project was to reconstruct Kesko office buildings into apartments. Most of the work was done under the ground water level which was challenging. The work started with jet grouting of the existing elevator shaft which had to be lowered. The soilcrete was constructed around the elevator shaft to make it watertight so that the work could be done safely inside the shaft without the ground water level problems. To secure the old concrete floor on place to install the RD 403 micro piles jet grouting was constructed. (KFS Finland Oy, 2019.)

- Ratina shopping centre groundworks, Tampere.

In this project the pit support close to the existing bus station was executed with jet grouting underpinning and anchors. Due to the excavation depth of 13 m with four rows of anchors the early design of 80 cm columns diameter was changed to 2m. A sealing slab with jet grouting was also necessary because the deepest part of excavation was under the ground water level. Therefore, columns of 3 meters were constructed to ensure cost and time effective construction. The total sealing slab was over 20000 m^2 which was one of the biggest sealing slabs executed with jet grouting in Europe. Figure 50 shows retaining wall executed with jet grouting Soilcrete and anchored. (KFS Finland Oy, 2019.)

Figure 50. Retaining wall executed with jet grouting Soilcrete and anchored. (KFS Finland Oy, 2019)

- Amos Anderson art museum, Helsinki.

New art museum was built under the Lasipalatsi square in the heart of Helsinki (Figure 51). The existing Lasipalatsi building was renewed and protected. Jet grouting was done under the foundations of Lasipalatsi base and the back of the sheet pile walls. Micro piling and anchoring were also used in this project. (KFS Finland Oy, 2019.)

- Figure 51. Amos Anderson art museum, Helsinki.

6 CONCLUSIONS

Jet grouting is the technique in which soil is stabilised with cementitious material to form a soil cement column. Jet grouting technique can be applied on broad a range of soil types and ground conditions. It provides flexibility in the execution of construction on the selected layer of soil in different positions, angle and extensively to a greater depth. Jet grouting has advantages over reinforcement and ground treatment method, which make it an ideal ground modification technique. The involvement of complex operations where erosion, grouting, mixing, replacing and filling occur at the same time makes this technique limited to understand the whole process accurately. The properties of soilcrete depend on soil types, the binder used and operational parameters which make it very complicated to calculate the exact soilcrete composition, diameter and its properties. The effects of these parameters on soilcrete’s physical and mechanical properties have to be fully understood first in order to conclude the jet grouting process properly. Laboratory tests are recommended to estimate the theoretical values required for the designing process. It is also strongly recommended to construct the trial soilcrete column directly to the site before the main jet grout operation. This will help to find out the results and operational parameters from the experiment whether it can be relied upon or not in the actual jet grouting project. Since jet grouting construction is not visibly possible to control like in other construction, the state of art in quality control process requires a great deal of planning, in monitoring and execution in every stage of construction process to achieve the desired outcome.

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INTERVIEW

Virolainen Matti. KFS Finland Oy. Interview 20.6.2019

Appendix 1

TableD.1 — Jet plant daily report

SITE:	ZONE	Pump type:
DATE:		Supervisor:
Shift from	to	Signature:

Supervisor instructions

	Value	Grouter
Water pressure (bar)		
Water flow (l/min)		
Grout pressure (bar)		
Grout flow (l/min)		
Air pressure (bar)		
Air flow (l/min)		
	Grout A	**Grout B**
Cement/batch (kg)		
Water/batch (kg)		
Batch mass (kg)		
Batch volume (l)		
Grout density (kg/l)		

Grout control

Time	Density (kg/l)

Grouter controls

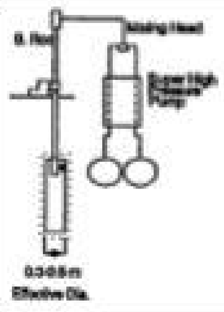
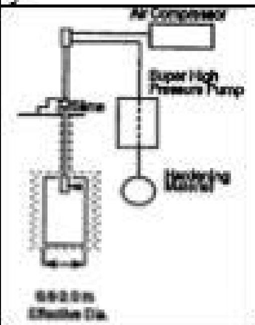
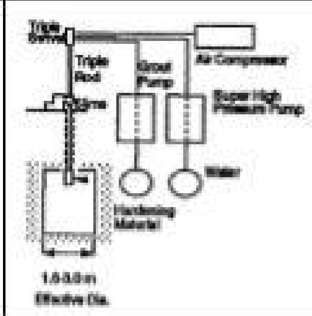
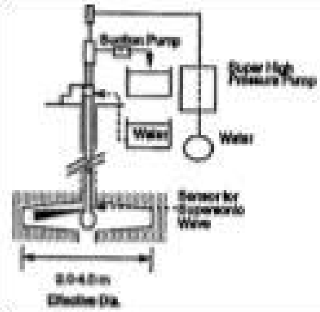
Column N°	Counter start drilling	Counter end drilling	Counter start prejetting	Counter end prejetting	Counter start jetting	Counter end jetting	Time start jetting	Time end jetting	Water pressure	Grout pressure

Stoppages N° batches prepared =

Time start	Time end	Nature of stoppage	Others observations
			Grouter: **Signature:**

Appendix 2

Difference between SSS- MAN method and other three jet grouting methods (Miki and Nakanishi, 1984)

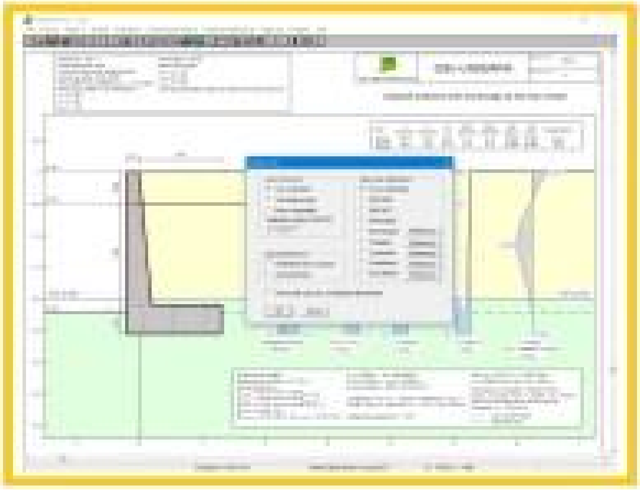
Method	Chemical churning pile method (CCP): a mixing method using a high speed grout jet	Jumbo Jet Special Grout (JSG): a mixing method using a high speed grout jet enveloped by an air jet	Column Jet Grout (CJG): a partial replacement method using a high speed water jet enveloped by air jet	Super Soil Stabilization Management method (SSS-MAN): reverse type replacement method using a high speed water jet enveloped by air jet
Schematic diagram				
Outline of the method	Uplift of a rotating horizontal grout jet with a supre high pressure (20MPa) mixes in-situ soil with grout and produces a cylindrically solidified body	Uplift of a rotating high speed horizintal grout jet enveloped by air jet mixes in-situ soil with the grout and produces a large size cylindrycal solidified body	Lifting of a rotating high pressure water jet enveloped by an air jet cut in-situ soil, which is partially removed by the uplift flow of the air and water. The excavation is filled with grout continuously supplied from a rod to produce a cylindrical solidified body	A pilot hole is drilled by reverse circulation, then a rotation super high pressure (60MPa) water jet enveloped by air jet is lowered removing the cut soil through the reverse rod to produce an excavateion which is filled with grout after confirmation of the size
Soil type	Cohesive soil (N<5), sandy soil (N<15)	Cohesive soil, sandy soil, gravelly soil	Cohesive soil, sandy soil, gravelly soil	Cohesive soil, sand soil, gravelly soil
Important efficiency	An improved diameter of 300-500mm with a relatively uniform strength with uniformity are attainable	An improved diameter of 800-2000mm and a high strength with uniformity are attainable	An improved diameter of 1500-3000mm and a high strength with uniformity are attainable	A large cylindrical solidified body with a diameter of 2000-4000mm is attainable. Concrete, clay, cement mortar, etc can be used as grout. The diameter of a body can be confirmed on the ground

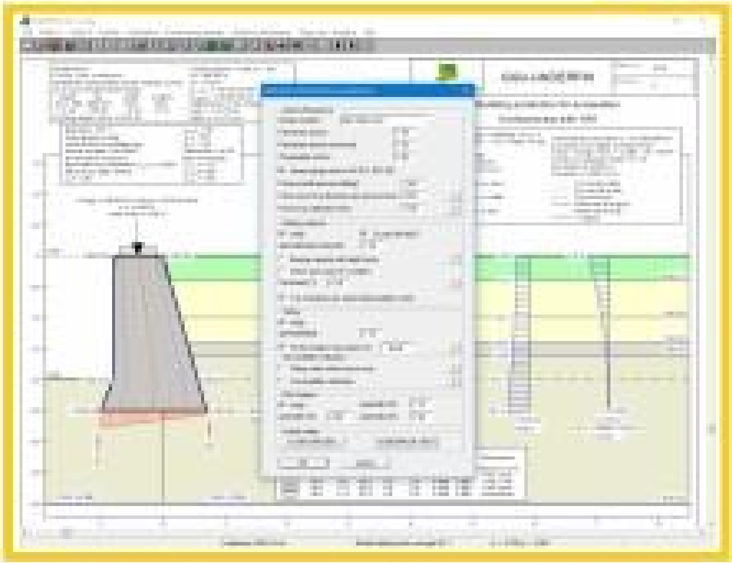
Appendix 3

Program Details

ARTICLE NUMBER
ggu-01-107

OPERATION SYSTEM
Windows 7/8/10





Description

GGU-UNDERPIN *– Analysis and design of underpinning bodies.*

Capabilities:

- *Choice of analysis using either partial safety factors to DIN 1054:2010, EC 7, Austrian Standard ÖNORM EN 1997-1 or global safety factors (DIN 1054 old)*
- *Bearing capacity safety and settlement analysis to DIN 4017 and DIN 4019*
- *Verification of sliding safety, hydraulic heave and buoyancy safety*
- *EQU analysis*
- *Inner stability analysis to DIN 4093*
- *Unreinforced concrete analysis*
- *System input using absolute heights*
- *Soil properties can be selected from an expandable database of common soils*
- *Consideration of active and passive berms*
- *Analysis using active earth pressure, at-rest earth pressure or increased active earth pr.*
- *Active earth pressure coeff. to DIN 4085*
- *Passive earth pressure coefficients to DIN 4085:2017, Streck, Caquot/Kerisel*
- *Consideration of hydraulic gradients on the active and the passive side*
- *Seismic effects via additional horizontal loads and/or altered earth pressure coefficients to EC 8*
- *Consideration of displacement and action boundary conditions, anchors and struts etc.*
- *Consideration of active and passive bounded and double-bounded surcharges*
- *20 area loads at any depth*
- *Consideration of prestressing of anchors and struts possible*
- *Verification of deep-seated stability with optimisation of anchor lengths*
- *Anchor steel design*
- *State variables can be selected for struts under load*
- *"5"" condition check to DIN 4017*
- *Limiting depth analysis using different methods*
- *Automatic search for earth pressure redistributions proposed by EAB*
- *50 additional earth pressure distributions*
- *Interface to the GGU-STABILITY (slope stability analysis)*
- *Choice of result presentation for earth pressure, water pressure, moment, shear force, normal force and bending line*
- *Graphical visualisation summarising various advancing and retreating stages*
- *Adapted standard, program name and version can be included in the General legend*
- *Freely definable positioning and sizing of graphical elements and legends*
- *Print or copy screen sections, e.g. for transfer to a word processor*
- *Integrated Mini-CAD system for additional annotation of graphics*

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