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Review of Jet Grouting Practice around the World

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ABSTRACT

This paper aims to make a historical review of jet grouting techniques and encountered problems at different sites in several countries. This review is a good guide to understanding the performance and limitations of improved soils or lands. The basic concept of jet grouting technology is to use cement as a binder to accelerate the hardening process of an admixture of material grout and soil. The different case history was conducted in both sand soil and clay soil in the horizontal and vertical direction. Other papers on field construction showed that the grout can be gelled within 5-10 minutes. Due to different cases and studies, these will help improve soil by supporting the foundation load with a minimal settlement. The Jet grouting technology can be used in difficult situations, confined and unconfined areas, or places with light equipment. Although the jet grouting technique is an ideal modification technique compared to reinforcement and ground treatment support or serves the foundation, Dams and excavations will save time and cost and increase the bearing capacity.

Keywords: Jet Grout, Quality Control, Permeability, Numerical Model.

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مراجعة الدراسات السابقة بالحقن الدفقي حول العالم

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قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

الهدف من هذه الورقة هو إجراء مراجعة تاريخية لتقنيات الحقن الدفقي والمشاكل التي واجهتها في مواقع مختلفة في العديد من البلدان. تعمل هذه المراجعة كدليل جيد لفهم أداء وحدود التربة أو الأراضي المحسنة. يتمثل المفهوم الأساسي لتقنية الحقن الدفقي في استخدام الأسمنت كمادة رابطة لتسريع عملية التصلب لمزيج من مادة الجص والتربة. تم إجراء تاريخ حالة مختلف في كل من التربة الرملية والاتجاه الأفقي والرأسي للتربة الطينية. من أوراق مختلفة من البناء الميداني أظهرت أنه يمكن تبلور الجص في غضون 5-10 دقائق كل هذه الامور ستساعد على تحسين التربة من خلال دعم حمل الاساس مع الحد الادنى للهبوط. وجد من خلال الدراسات الميدانية المختلفة بامكانية استخدام تقنية الحقن الدفقي في الاماكن الصعبة المحصورة او غير المحصورة باستعمال معدات خفيفة الوزن. و على لارغم من ان تقنية الحقن الدفقي هي تقنية تحسين مثالية مقارنة بانواع مثل تسليح التربة و معالجة الاساس كل هذا سيساعد في دعم أو خدمة الأساس والسدود والحفر وكل ذلك سيوفر الوقت والتكلفة ويزيد من قدرة التحمل

الكلمات الرئيسية: الحقن الدفقي, ورقابة الجودة, والنفاذية, موديل عددي.

1. INTRODUCTION

The most efficient method to make land construction feasible from technical and financial standpoints is ground improvement. The purpose of improvement is to increase the shear strength, bearing capacity, stiffness, and stability of the earth or the structure, and to minimize undesirable properties such as settlement, liquefaction, collapse, permeability, and swelling. Many techniques have been used to change unsuitable lands to lands suitable for construction. Different kinds of ground could be improved using various techniques and materials are as follows, as shown in **Fig. 1**:

1- Shallow and deep compaction (**Alimohammadi et al., 2022)**
2- Over excavation and replacement **(Ahmed and Hamza, 2015),**
3- Deep replacement, **(Güllü et al., 2017)**
4- Drainage and dewatering **(Martin et al., 2019)**
5- Preloading **(Chu and Yan, 2005)**
6- Ground reinforcement and full reinforcement **(Al-Adili et al., 2012)**
7- Deep mixing **(Al-Hadidi and AL-Maamori, 2019)** and grouting **(Ali and Yousuf, 2016)**

Grouting techniques were used before the 18th century and continued to develop through the 19th century. Some methods involved using a grouting suspension containing a small amount of lime or cement injected into joints under dams to reduce leakage. Portland cement was initially used as a grout for more than 150 years in Europe and more than 100 years in the United States of America **(Juge, 2012)**. The geotechnical division of the American Society of Civil Engineers defines grouting as the injection of materials into the formations of soil or rocks to decrease the hydraulic conductivity and increase the mechanical rigidity of the soil. The main grouting techniques are **(Bogati, 2019)**:

1- Chemical grouting,
2- Bio-grouting,
3- Compensation grouting,

4- Compaction grouting,
5- Permeation grouting, and
6- Jet grouting.

This article reviews jet grout techniques and how they started, developed, and progressed.

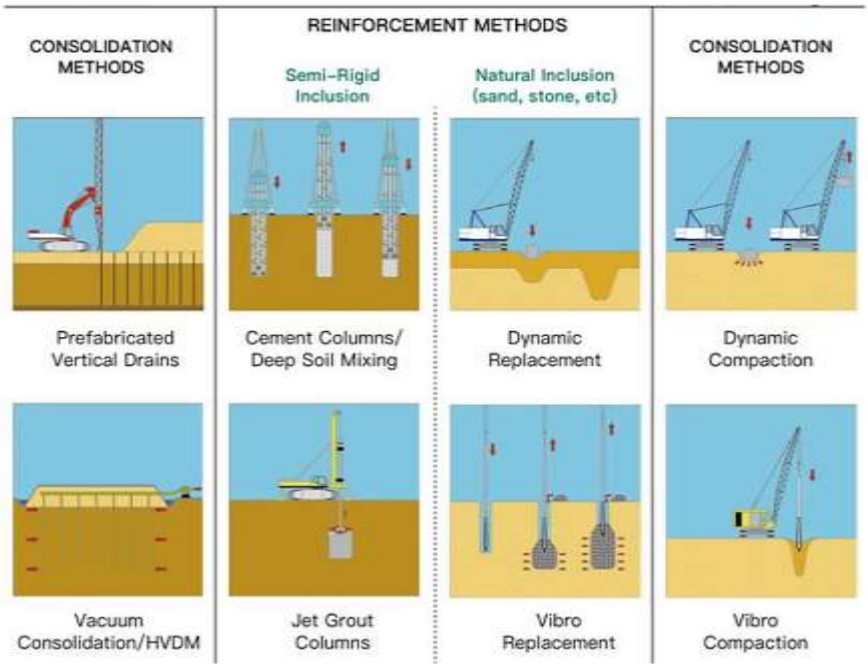


Figure 1. Types of strategies for improving soils **(Geoharbour, 2017).**

2. JET GROUTING TECHNIQUES

In the late 1960s, Farmer and Attewell used high-speed jets to cut rocks and materials that resemble rocks. This technique inspired a group of Japanese specialists to adapt it to improve soils. **(Nakanishi, 1974)** used the first version, known as chemical churning pile (CCP), which utilized a chemical binder and years later used water-cement grout. **(Xanthakos et al., 1994)** developed a technique for Jumbo Special Pile (JSP) and improved the method to reduce the dimensions of the jet grouting element.

Initially, jet grouting was primarily used to improve the subsoil under the major foundation systems and later became popular in Europe, such as Italy United Kingdom, and Germany.

In 1980, jet grouting was first used in the United States of America on a limited scale. After that, it became popular in the United States of America, Canada, South America, and worldwide. Meanwhile, jet grouting gained popularity in Brazil **(Giorgio Guatteri, 1988)**. Jet grouting is currently employed on a global scale **(Fang et al., 1994),** as shown in **Fig. 2**, for the following reasons:

1. It requires drilling small holes, with limited disturbance to the surrounding soil, to create large columns of cemented material,
2. Elements with high mechanical strength and low permeability can be formed by assembling grouting columns of varying sizes and forms,

3. Metal or fiberglass can reinforce the jet grouting columns to give the needed flexural and tensile resistance. Such practice helps to solve geotechnical problems such as supporting underground excavation, creating water cutoffs for hydraulic reservoirs, reducing settlement, and increasing the bearing capacity of new foundations or existing ones, and
4. Jet grouting can be used in difficult situations with light equipment in confined or open areas or places with difficulty to reach, so it can be utilized not only for new construction but also for protecting or repairing existing structures.

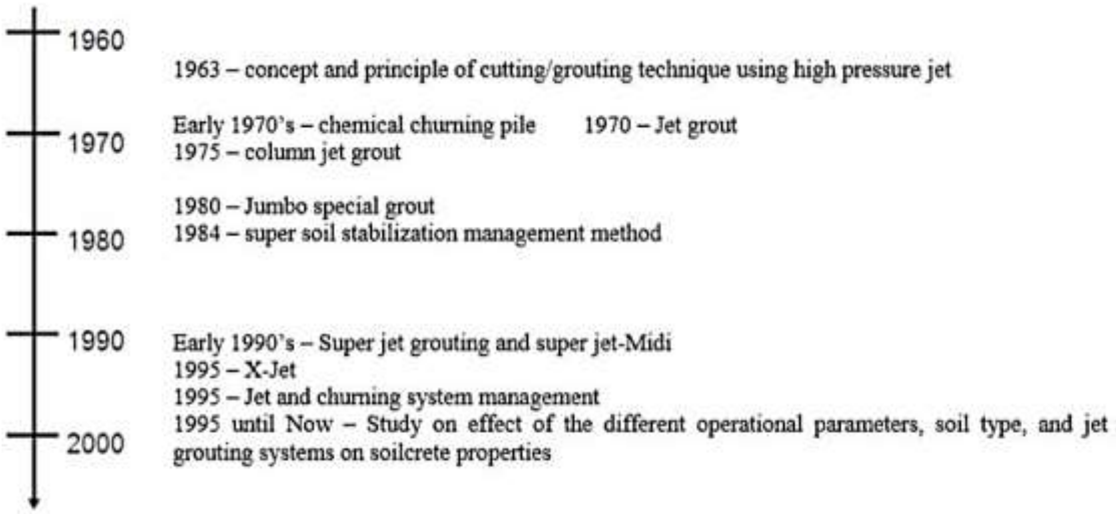


Figure 2. History of the development of Jet Grouting **(Ji, 2008).**

2.1. Application of Jet Grouting

Earlier, the use of jet grout was to improve the ground properties such as strength and stiffness, as shown in **Fig. 3**, for instance:

1. Fill massive voids in rocks and soils,
2. Obstruct water flow and decrease seepage,
3. Form-bearing piles,
4. Strengthen soils and rocks,
5. Repair settling damage of structures,
6. Support soil and create secant-pile walls, and
7. Install anchors and tiebacks and improve their capacity.

Later it was also used to repair structures **(Juge, 2012)** such as:
1. The casting of preplaced aggregate concrete,
2. Filling cracks and splits to repair timber structural components,
3. Repairing cracks in subsurface concrete structures that need welding,
4. Disintegrating concrete or masonry components returning to a monolithic mass, and
5. Protecting tendons and anchors from corrosion.

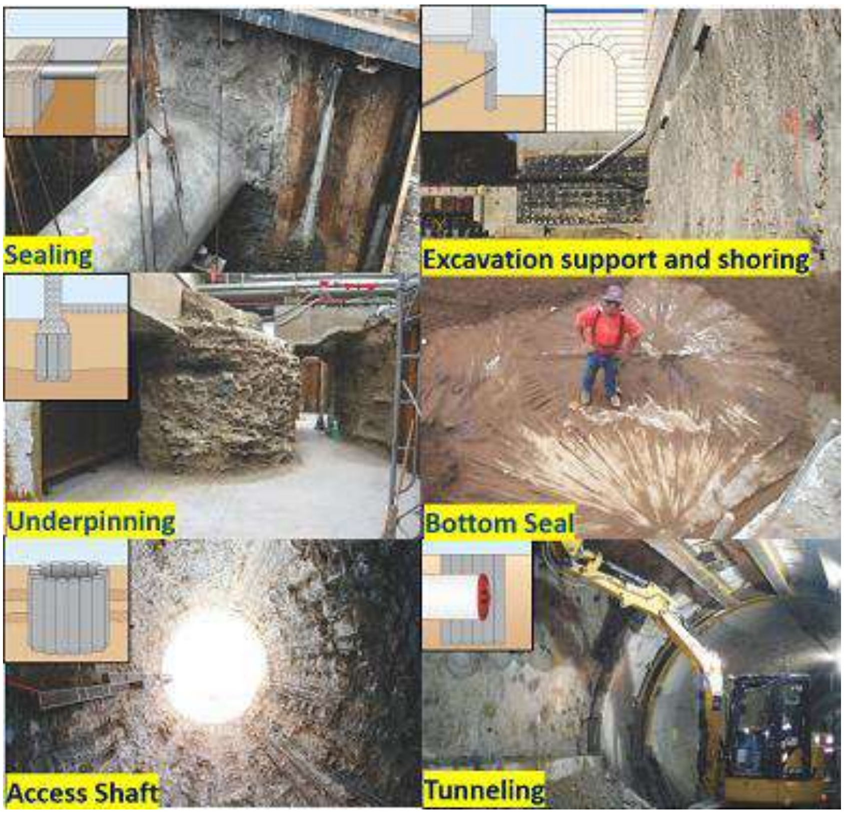


Figure 3. Application of Jet Grouting **(Manne et al., 2020)**.

2.2 Application Due to Type of Soil

The main advantage of the jet grouting technique is its applicability for all types of soils ranging from soft clay silt to sand and gravel. Also, it can be applied to soils with non-uniform and fluctuating layers containing organic compounds. **Figs. 4 and 5** show the workability areas of jet grouting.

2.3 Application of Jet Grout with Different Uses

Among the various approaches for enhancement, jet grout occupies a unique place. In 1980, Guatter and Guattari utilized jet grout in South America for the first time in the Sao Paulo water and sanitation department to repair the collapsed tunnel crown for the Sanegran Interceptor tunnel. Due to environmental concerns, they used a Chemical Churning pile and water-cement grout instead of chemical grout. Later on, the Sao Paulo municipal office wanted to construct a trapezoidal water channel to convey runoff by treating a 5-m soft silty clay soil using Jumbo jet grout (JJG). Also, General Motors of Brazil wanted to expand its manufacturing capabilities by building ten new auto body stamping mills using JJG.

(Taha, 1992) found that using jet grout can be effective with or without little interruption to the services or utilities near the site of Florida Suncoast Dom Stadium in Tampa, Florida, as shown in **Fig. 6**, using a triple-rod system to stabilize the soil. From such a technique, the safety factor increased from 0.984 to 1.1, soil permeability was reduced to a value as low as 10^{-11} cm/sec, and the compressive strength value was as high as 48.263 kN/m^2.

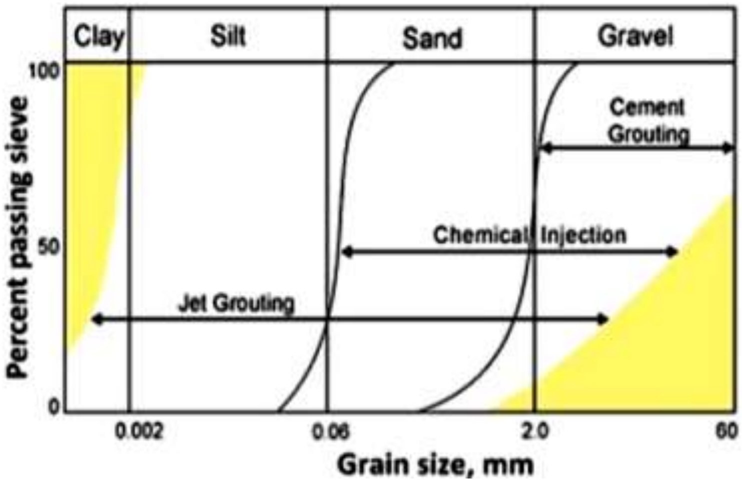


Figure 4. Workability area of Jet Grouting **(Baker, 2012)**.

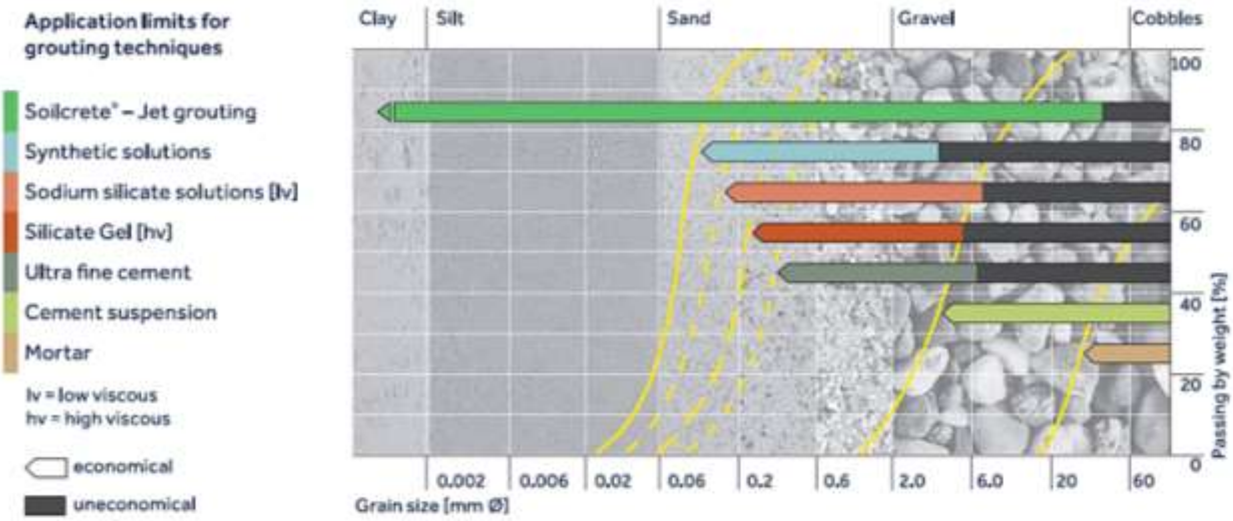


Figure 5. Grouting Application Limits in Comparison to Jet Grouting **(Keller, 2017)**.

Figure 6. Florida SunCoast Dom Stadium. **(Taha, 1992)**

(Fang et al., 1994) examined jet grouted's mechanical characteristics samples of soils related to Metropolitan Taipei, which suffers severe congestion and parking issues due to the escalating volume of vehicle traffic, and due to the nature of the ground, the best suggestion was jet grout. The researchers concluded that high dry density resulted in a high uniaxial compressive strength, modulus of elasticity, failure strain, and tensile strain in soilcrete. **(Lunardi, 1997)** gave details about applying the jet grouting technique and its uses in Italy in various civil engineering works, such as earth retaining structures of the building of Milan underground railway. Slope stabilization at Gela involves installing horizontal drains to prevent landslides brought on by erosion at the toe by groundwater seeping along the surface of an impervious layer beneath. The Italian engineer used jet grout in tunnel construction.

(Croce et al., 2000) used single jet grout at three sites with different types of soil. They found that single fluid jet grout is efficient for coarse-grained soil. They also found that the diameter was reduced with decreasing soil grains, and the column diameter for granular soils cannot be correlated with SPT blow. They found that the treatment is very effective in sand and gravel, but the clean gravel permeability is not reduced with jet grout.

In Turkey, **(Saglamer et al., 2001)** gave complete details about the largest jet grout application for the Ford Otosan Automobile manufacturing site, which was subjected to an earthquake. Different quality controls were applied, including an integrity test, coring, uniaxial test, and unconfined compression test. They also discussed the case of another project in the same area using jet grout and different types of foundations. Quality control was the mean concern, together with the kind of jet grout, the composition of grout, pressure, number and size of nozzles, speed of lifting, and rotation.

(Durgunoglu et al., 2004) used the jet grouting technique as an improvement method to reduce the potential for liquefaction-related damage in sandy soils and strain-related problems in soft clays. Afterward, Kocaeli's earthquake (M=7.4) attacked northwestern Turkey and caused significant damage in urban and industrial areas along Izmit Bay. The treated site consisted of stiff layered clay and medium to dense sand, and a mat foundation was laid out above the treated soil with jet-grouted columns. From the treatment, it was found that the improvement by jet grout yielded an area replacement ratio equal to 7-10% effective against possible damage induced under earthquake due to liquefaction and cyclic mobility potential of the soil. Limited structural damage was observed at a nearby structure found in the untreated area.**(Rollins et al., 2008))** studied lateral-load test, which was performed on a full-scale model of a pile cap on the clay of multilayered soil and found that 20% by weight of cement content was enough to increase the compressive strength of soft plastic clay to 4500kPa (the values ranged from 40-60 kPa without improvement). The stiffness of the pile group due to jet grouting increased from 140 to 700 kN/mm. Increasing lateral resistance due to jet grout for pile-group foundations is an economically viable cost.

Tuttle Creek Dam **(Stark et al., 2009),** located on the Big Blue River near Manhattan, Kansas, which constructed by the U.S. Army Corps of Engineers. The Corps developed a program to assess the recent earthquake and its effect on the dam's stability by using double and triple jet grout downstream, as shown in **Fig. 7**. Jet grout columns may create a continuous, largely impenetrable wall. It is necessary to consider the column's diameter, energy correlations, and evaluation of the treated soil's quality, including untreated soil. Technically, jet grouting is more difficult and less forgiving than other improvement methods. **(Correia et al., 2009)** studied the mechanical properties of jet grouting columns used to improve the soil in a subway station in Barcelona, Spain. The samples obtained by two methods, a core sample, fresh jet material, and laboratory mixtures, revealed a similar performance. Still, the most difference is E_{50} of the fresh sample and the core sample, as shown in **Fig. 8**. The difference in moduli may be related to a disturbance in the material (cracking and micro-cracking) during extraction of samples (the cracks have a stronger influence on the determination of modulus than the evaluation of the uniaxial compressive strength).

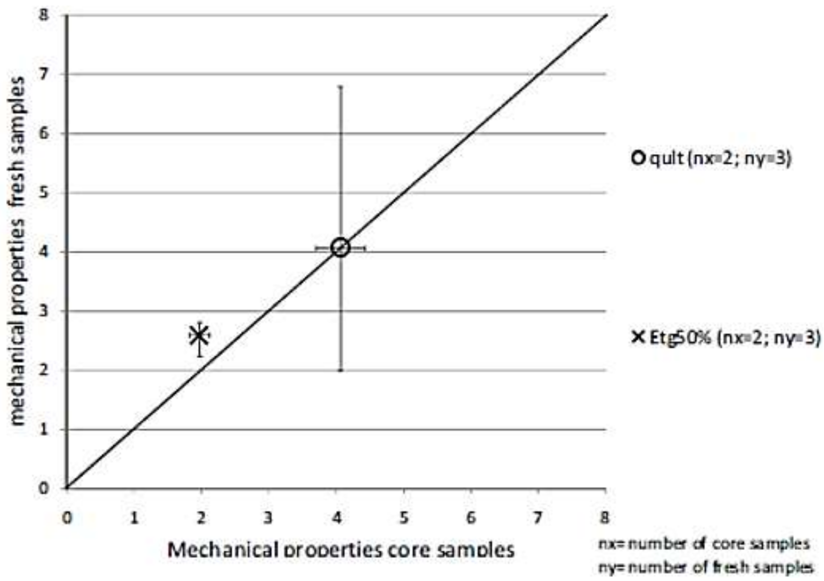
(a) **(b)**

Figure 7. (a) View of Tuttle Creek Dam (b) Downstream of the Dam with Jet Grout **(Stark et al., 2009)**.

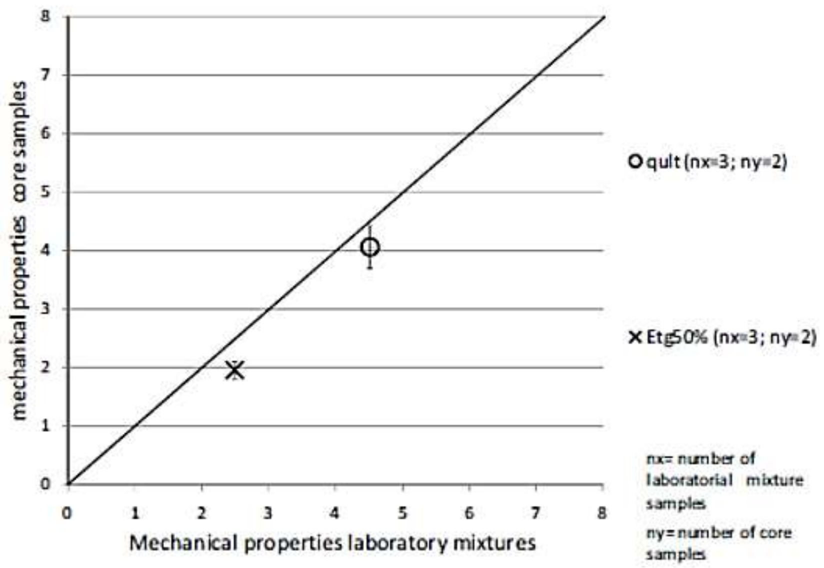
(Modoni et al., 2010) compared experimental investigations and numerical simulations by back analysis of the reaction of axially-loaded jet grouting columns to load settlement. From practical work, jet grouting columns can support axial loads (20–30%) greater than those anticipated for bored piles with identical average dimensions. According to a numerical study, the disparity is caused by the columns' erratic form. Serviceability is the most stringent limit criterion to consider while designing a foundation. The acceptable settlement (W/D=0.05) was used as the basis for the limit serviceability study.

(Nikbakhtan et al., 2010) used jet grouting technique in Shahriar dam (Iran) and studied the whole parameters that affected the stabilization of the dam and specified the accurate parameter using a triple fluid system. Because of the basal clay layer's poor shear strength and the constrained area between the upstream cofferdam and the main dam, excavation slopes must be rather steep. Different grouting parameters (grout pressure, lifting speed, rotation speed, water pressure, water flow rate, and water cement ratio W/C) were used in the job, taking into account their effects on the specifications of the generated soilcrete columns. Accordingly, the soilcrete diameter and the UCS uniaxial compressive strength were increased.

(Hamidi et al., 2010) successfully used jet grouting, including many functions such as enhancing bearing capacity, retaining the soil, and constructing impermeable barriers to stop water flow during construction. They used three types of jet grouting, namely single, multiple, and triple, in different boreholes and locations. Also, the design implemented a finite element analysis to verify stress and deformation.



(a)



(b)

Figure 8. Comparison between (a) the core sample and (b) laboratory mixtures **(Correia et al., 2009)**.

(De Oliveira, 2011) used the jet grouting method to treat the soil for the port in Navegantes, south of Brazil, and found it effective. The area has layers of soft soil with organic material. In his research, he conducted finite element analysis using reinforcement and without reinforcement, and his simulation focused on the existence of organic materials. He concluded that physical and chemical tests should be done for the mix of soil and cement, and a technological control should be run during jet grouting operation for soil

cement material and compared the results with samples collected directly from intact columns.
A York Sewage System in Ontario, Canada **(Chuaqui et al., 2012)** used the double jet grouting method to form watertight and continuous soil-cement elements at shaft/tunnel junctions. The purpose was to reduce permeability, stabilize soil at the tunnel, and provide groundwater containment. Jet-grouted soil's unconfined compressive strength (UCS) ranged between 4.6 and 9.7 MPa compared to a minimum of 2 MPa. The average permeability was less than $1*10^{-5}$ cm/sec.
(Bzowka, 2012) used jet grouting columns in the Bojszowy Nowe site in Poland. He studied the loading results and examined uplift tests for jet grouting columns and the interaction and influence of soil conditions on the bearing capacity of columns and settlement. The strength parameter for jet grouting material was calculated for reinforced and non-reinforced columns.
(Juge, 2012) studied the modeled mechanical behavior of injected soil to establish several design characteristics in engineering, such as the extent of the injected zone, poroelastic cement zone, and injection rate. The second part of his study involved analyzing the soilcrete formed in the injected area by measuring its uniaxial compressive strength.
(Shinsaka and Yamazaki, 2013) studied the importance of using grouting energy to achieve efficient construction with quality control. To accomplish that, they developed a highly efficient jet grouting device with two oppositely-located nozzles and used it as a full-scale model with a large diameter. Such a technique provided economic efficiency and lower environmental impact than the conventional method. Also, they developed eroding measurement technique, as shown in **Fig. 9**, for sound collection during jetting to ensure the quality of column diameter when installed in special soil conditions.

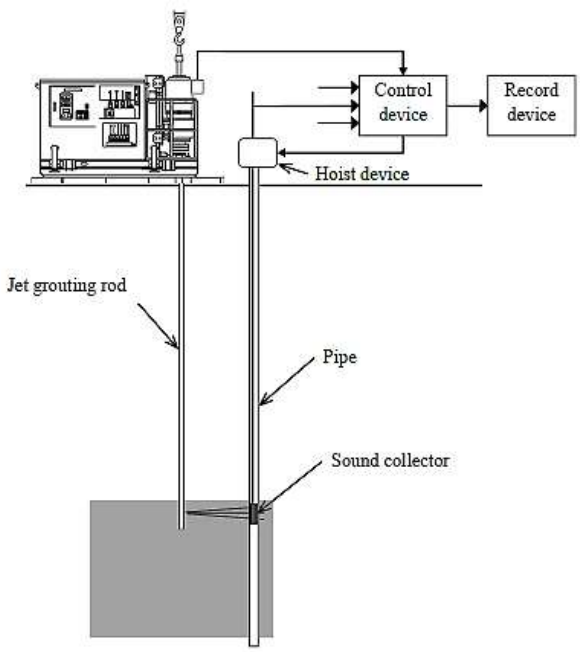


Figure 9. Eroding Measurement System **(Shinsaka and Yamazaki, 2013).**

Before 2013, no successful trials were done in Vietnam. But, later on, a single jet grout was used in Ho Chi Minh City on soft-clay soil to construct tunnels between big cities with four soil columns **(Tran-Nguyen et al., 2013)**. From field experiments and cored samples, they concluded that:

1. Single jet grouting worked well in the city conditions,
2. A single jet grouting system can create soil columns with a diameter of 1 m or more in soft soils,
3. The operating parameter of the grouting system can easily customize the diameter of soil columns,
4. The jet grout system used can form a soilcrete having a compressive strength of around 1 MPa at a curing time of 28 days, and
5. The water-cement ratio of 1:0.7 was more appropriate to generate cement slurry for a single jet grout at that site.

(Shen et al., 2013) used three types of jet grouting and compared them with applying a generic method for estimating the diameter of jet grout columns in relation to existing models of turbulent kinematic flow and soil erosion, as shown in **Fig. 10**.
The analytical equation for estimating the column diameter:

$$D_o = 2R_c = 2\eta * \chi_l + D_r \quad (1)$$

where:

D_o	=	the column's calculated diameter,
R_c	=	determined the column's radius,
H	=	Reduction coefficient that takes the time of injection into account,
χ_l	=	the maximum erosional distance, and
D_r	=	The monitor's diameter.

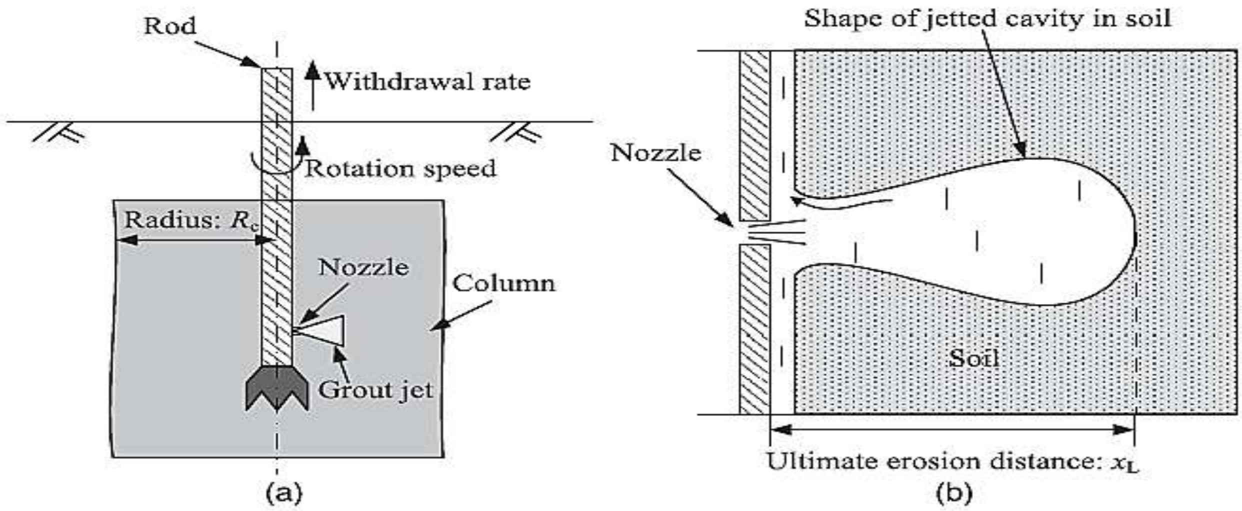


Figure 10. Schematic view of jet grouting models (a) Cross sectional view for grout rod, (b) soil erosion **(Shen et al., 2013).**

This analysis applies to all jet grouting techniques. It considers all operational factors (number of nozzles, the diameter of nozzles, flow rate of injected fluid, properties of injected fluids, rotational speed, and soil type). Moreover, this technique assesses soil erodibility and considers how injection duration affects erosion distance. This method showed a good agreement between calculated and measured diameters.

Due to the collapse of a secure place, they suggested using a jet grout block for the four underground parking uplift piles along the tunnel **(Ni and Cheng, 2014)**. They suggested using saturated silty-sand soil to form the grout block. Other quality control techniques, including soil flow rate and spoil return, were also adopted. Because the volume of returned spoil is more significant than that of jet grout in that project, the ratio of spoil to grout is intended to be 1.3 for clayey soils and 1.1 for sandy soils. This range was recommended by (JJGA) as shown in **Fig. 11**.

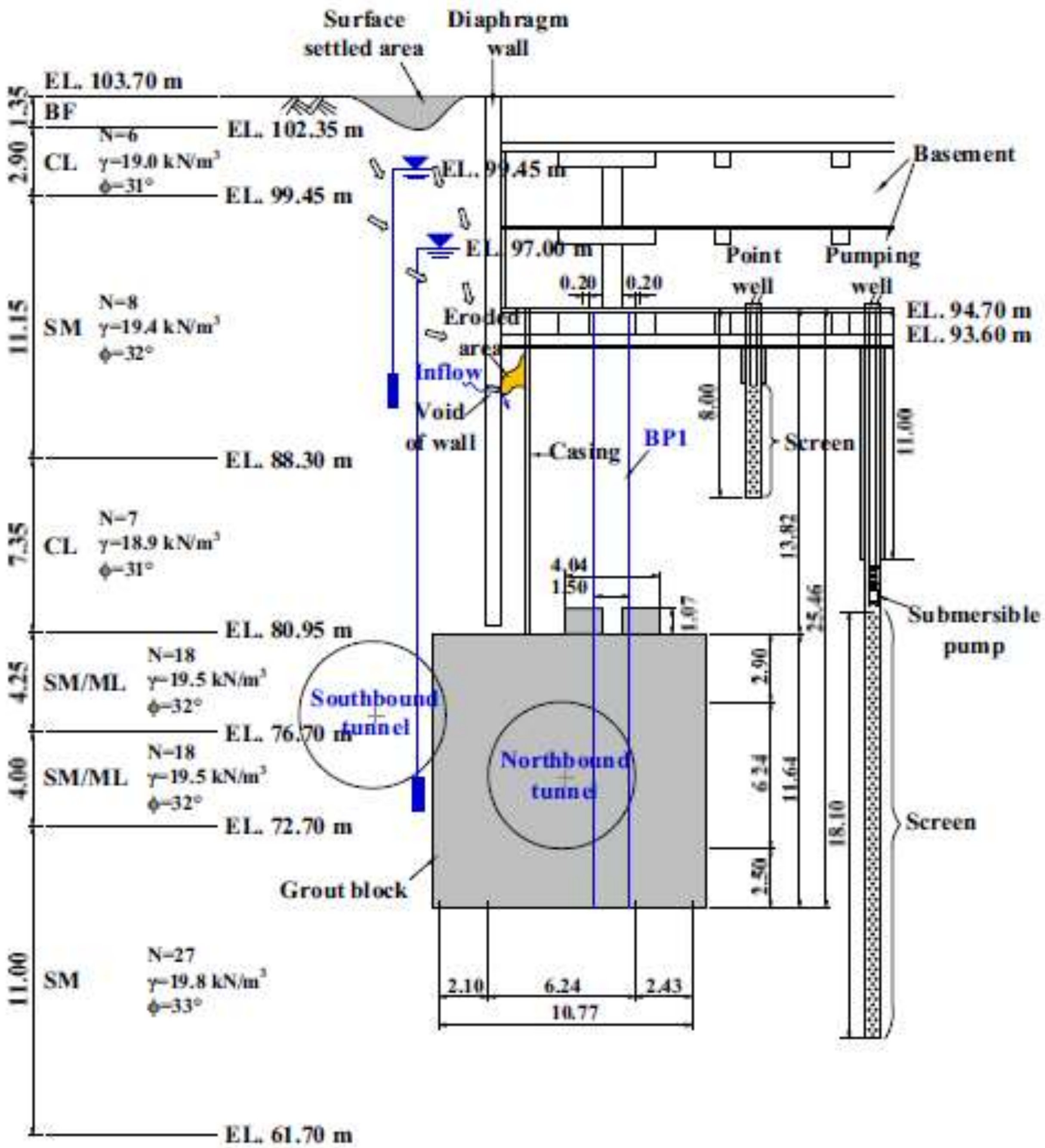


Figure 11. Section profile with grout block of the well **(Ni and Cheng, 2014).**

From that project, the following conclusions were drawn:

1. Sand boiling or groundwater inflow can be detected by monitoring the grout volume,
2. By using a back calculation to determine the value of the mean spoil density and spoil flow, the estimated column diameter in the field was approximately 1.56 meters, or 2.5%, less than the design diameter of 1.6 m, and
3. Additional infill columns are jet grouted to improve the quality of the jet grouted column; however, this requires higher cost and more time and work to move the grouting machine.

(Rabaiotti et al., 2015) used jet grout for soil stabilization**.** The excessive pre-stressing of retaining walls and soil in an excavation pit and the following pressure released to the retaining structural element are two potential issues from jet grouting, as shown in the section profile in **Fig. 12**.
The project was located in the city of Lucerne, Switzerland. An extensive analysis was done to determine what caused the increased strut forces observed in the braced excavation. The result demonstrated that diaphragm walls and other soil-embedded structures could be pre-stressed by jet grouting in soft soil. A retaining system supported this additional stress. Thus, using a proper jet grouting technology can reduce the risk of installing the holding system after allowing for an elastic rebound.
(Nikbakhtan et al., 2015a; Nikbakhtan et al., 2015b) were the first to use a mathematical model (Sum of squared deviations, SSDs) with Matlab software. The second group of researchers used ANN to predict the diameter and to develop an optimal neural network model to reduce the need for trial jet grouting (Triple fluid system) and optimize the cost and time needed for mining in civil projects. The two groups of researchers used all data required from Shahriar and Nian dams in Iran.
(Debost et al., 2017) at the Barangaroo project in the old city of Sydney, the site was an ancient gas highly contaminated work site with hazardous substances. Double jet grouting was considered highly dangerous because of the large quantities of airborne pollutants inside the tent. Accordingly, single jet grout with a jet plus monitor using moderate energy was utilized at that site. The chosen binder was a mixture of 60% ground granulated blast furnace slag and 40% Portland cement. The site contains sand and gravel (sandstone types IV & III at different depths) with a minor quantity of clay. Environmental management methods guaranteed that air levels were consistent with expectations and safe for personnel and the general public in the vicinity of the site.
In Brazil, a routine inspector discovered water resurgences at the toe of a tiny embankment dam (Ribeirao do Gama) **(Ludemann et al., 2018).** The consultant and geotechnical engineers first suggested using jet grouting to construct overlapping columns to prevent groundwater leaking. To reduce the instability of the jet grouting treatment of earth mass, certain precautions were adopted as advised by **(Croce, 2012; ABEF, 2012)** to avoid deviation and diameter variation of the columns. Jet grouting and a downstream drainage system helped even after the treatment. Such collection was required because the jet grouting impervious system failed, and the downstream drainage system should be able to collect subsequent flow from the collapsed system without negatively affecting the embankment's stability.

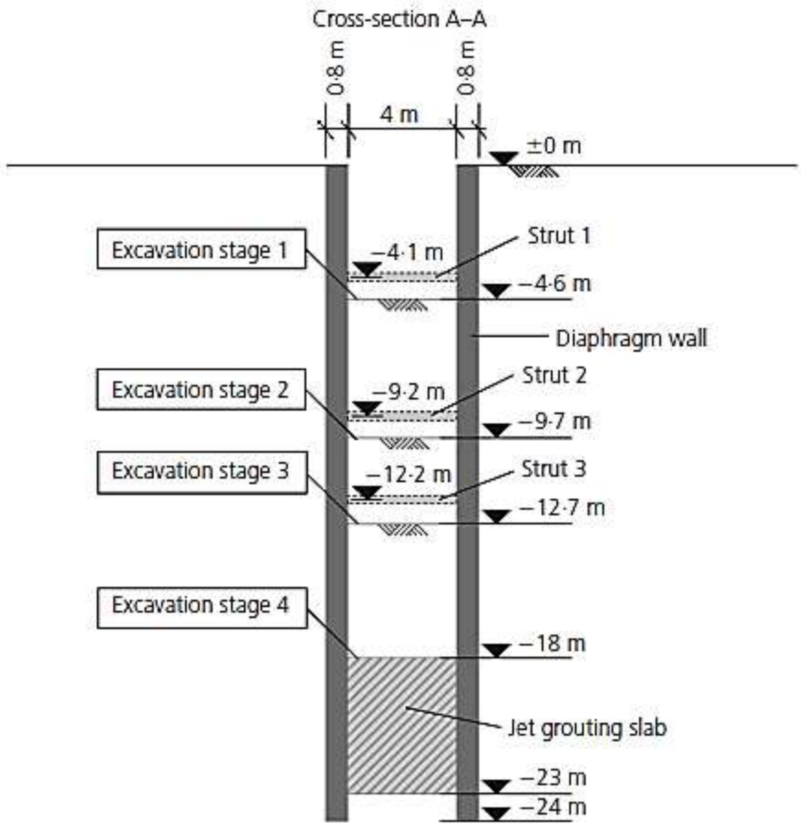


Figure 12. Cross-section well profile with strut, excavation, and jet grout slab **(Rabaiotti et al., 2015).**

(Njock et al., 2018) analyzed the advancement and application of jet grouting technology by using some basic ideas and case examples from various nations and gave details about twin jet grouting. The researchers found that double jet grouting is twice more efficient than the mono-fluid system for the same jetting energy. The triple fluid system improved the construction speed. Their research concluded that for the same cement ratio, the unconfined compressive strength, UCS, when using high-grade cement is higher than the UCS of low-grade cement; conversely, the UCS decreased as the water-cement ratio increased. The effectiveness of the double jet grouting method depends upon several criteria utilized in the mixtures, both in terms of construction and quality control and economic rationale. These criteria are the cement content, the water-to-cement ratio, and the cement-to-glass-slurry ratio.

(Kimpritis et al., 2018) focused on the quality control of using jet grouting operations. One of these controls is the diameter of the constructed column. There are several methods to find column diameter; some of them are:

1. Excavation,
2. Core drilling: vertical or inclined,
3. Thermic method: by monitoring the local temperature while the binding agent is curing at the center of the jet-grouted column,
4. Jet grouting column calipers: shortly following construction, a device was lowered into the newly jet-grouted column **(Getec, 2004)**,

5. Vertical painted bars are set into the ground at a distance around the column's center that is nearly equal to the expected diameter of the column,
6. Hydrophones are installed in the ground. Based on the sound strength captured and the shape of the resulting sound diagram, the column diameter is approximated,
7. Models of empirical calculations that take into consideration the density of the soil spoil and grout mixture that is brought to the surface during jetting operations,
8. Geophysical methods,
9. Wave analysis method based upon elastic wave analysis,
10. Using a semi-empirical formula based upon turbulent kinematic flow theory that evaluates the high-pressure injection grout's ability to erode, and
11. Theoretical models form an analytical approach's foundation **(Modoni et al., 2006)**.

The use of jet grouting for the building of Analipseos station, which is a component of the Thessaloniki Metro in Greece, and the use of coring and thermal methods are shown in **Fig. 13**. The soil beneath the station has layers of medium-density to dense clayey, silty gravels with sand in addition to a greater thickness of clay and silt.

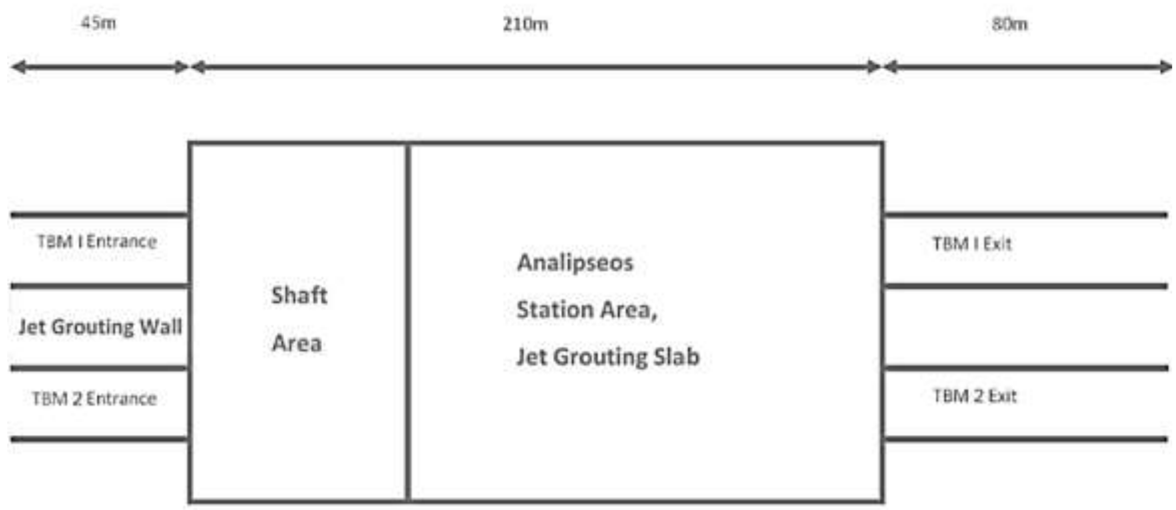


Figure 13. Analipseos Station Plan **(Kimpritis et al., 2018).**

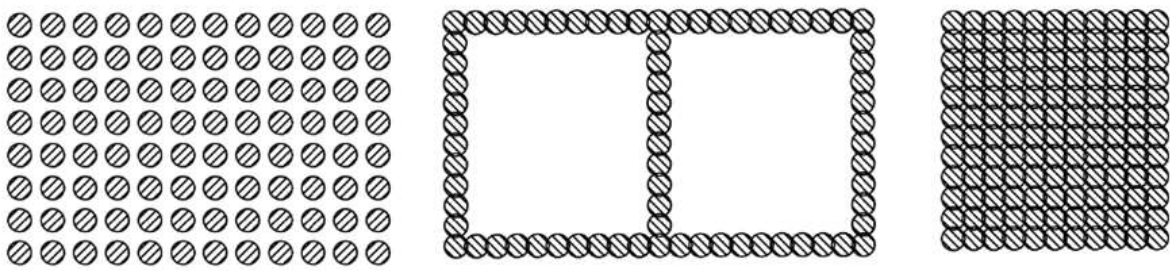
Applying the thermic approach to the site indicated that the predicted diameter was within ± 12% of the actual diameter after correlating the data from both sources, over-predicting in clay/silt soils and under-predicting in sand/gravel soils.
(Akin et al., 2019) performed a standard penetration test (SPT) and multi-channel analysis of surface waves (MASW) at two sites. The researchers examined the changes in soil parameters in the compression zone following jet grouting in sandy and clayey soils. Sandy strata exhibited a higher rate of compression zone enhancement than clayey deposits. Moreover, they compared the results with those obtained from finite element analysis using Rocscience (RS2 v 9.0). **(Modoni et al., 2019)** gave attention to the effects of jet grouting systems on the mechanical properties of the materials formed when using single and double jet grouting methods on sandy and clayey soils. Different grout compositions and injection parameters indicated that clay soil's strength is lower than sand's; this is due to the difficult erosive capacity of the jet grout in plastic soil because of

the complete mixing of the binding agent and the original soil particles. In addition, using twin jet grouting demonstrated the good impact of air in increasing column diameter. Consequently, the double fluid system has a lower uniaxial compressive strength than single fluid materials.

(Gürbüz, 2019) studied using a single jet grouting system to preserve the historical and culturally significant buildings nowadays under dynamic loadings. The study aimed to improve and evaluate the strengths and subsoil conditions, especially with serious ground problems such as liquefaction during earthquakes. The research used the Vali Konagi building in the Konak district of Izmir because of the standard penetration test and under (0.45 g) loading, the liquefaction problem could be observed. As shown in **Fig. 14**, Jet grouting cells were applied on sandy soil, and the numerical analysis results of improved and unimproved soils were compared using a finite difference program (FLAC-2D). Under the improved soil conditions, excess pore pressure did not surpass the effective stress. Thus the liquefaction was not initiated. Deformation was prevented from exceeding permissible limits. In his study, the jet-grouted cells were created to demonstrate greater confinement in the soil and increased shear capacity depending upon the features of the jet-grouted material.

(Al-Kinani, 2019) described the fieldwork of using a double jet grouting technique in south Iraq on the right bank of the Euphrates River in Al-Nasiriyah because of poor engineering properties. He compared field data with theoretical approaches using the finite element method using Plaxis-2D software.

In general, constructing one jet grout column requires 1-2 hours, while the total cost is approximately one-third of the board pile. Settlement curves showed that the average head settlement and ultimate axial capacity for a single and a group of soil-cement grout columns are increased with the number of jet grout columns and piles in the group. Due to jet grouting, the soil's unconfined compressive strength rose from 36–40 kPa to an average of 4000 kPa. The average cohesiveness of soil treated by jet grouting column was raised with increasing average unconfined compressive strength and jetting pressure of jet grouting soil.



a) discrete column b) cell column c) block type

Figure 14. Different applications of jet columns **(Gürbüz, 2019).**

(Manne et al., 2020) studied the various geotechnical issues and indicated that jet grouting could be successfully used if the issue is correctly identified and the required mitigation measures are applied. They stated that the design should consider jet grouting elements' strength, deformability, and potential diameters in the in-situ soils. Furthermore, they described a stringent quality control system to guarantee the target outcome.

(Moayed and Azini, 2020) described the jet grouting technique that was used in a project in the south of Iran. They specified the factors that affect jet grouting operation: compressive strength of jet grouting column, specific gravity, soil behavior model, and elastic modulus of jet grouting column. Quality control was used to define the diameter of the column, and shear wave testing and pile integrity test were used to compare the diameter with the results of the numerical solution using the Plaxis program and Mohr-Coulomb behavior.

(Lees and Gurpersaud, 2020) found that the double jet grouting technique was successfully applied to modify and stabilize soils in two projects, one in Winnipeg and the other in Calgary in, Canada. Jet grouting created a bottom seal and perimeter water cut-off wall with technical considerations such as quality control. The soil in one site was silty sand to sand with low SPT, and the other one was sand varying from loose to compact with some silt lenses. They concluded that the need for remedial and supplemental jet grouting elements should be reviewed during the execution of the project based on data acquisition reports.

(Tran-Nguyen and Ly, 2020) utilized the pilot soilcrete column created by jet grouting at the Vam Dinh bridge abutment, in Dong Thap province in the Mekong Delta in Vietnam, with layered soil varying from medium clay to soft clay. They also used quality control assessment with jet grouting and a height-to-diameter ratio (H/D) of 2-2.5. Due to the non-uniform soil layer, the column cross-section did not circulate, and the unconfined compressive strength ranged from 1.6 to 2.2 MPa, which was also higher than the anticipated 0.5 MPa. The secant modulus (E_{50}/q_u) ranged from 57 to 231, indicating an excellent improvement to soft ground to reduce settlement.

(Aksoy, 2020) compared the behavior of different soils clayey, sandy, and wet sandy soils and three values of bar pressures, namely: 300, 350, and 400 bars, by using jet grouting in the field in the region of Gaziantep in Turkey. All physical and mechanical tests were done. Seven jet grouting columns were used after completing grouting cores and were tested. The following conclusions were drawn:

1. The compressive strength of sandy soil was much higher than that of clayey soil,
2. As the time of curing increased, the compressive strength of both soils increased,
3. The diameters of all samples increased as the pressure increased,
4. Sandy soil (dry and wet) requires a larger diameter than clay soil because water-cement injection works better with non-cohesive soils than cohesive ones. The void ratio in the sand is large as compared to that of clay soil. Thus, the voids were filled with the injection material, and
5. Sandy soil showed a good binding effect with water cement solution than clayey soil.

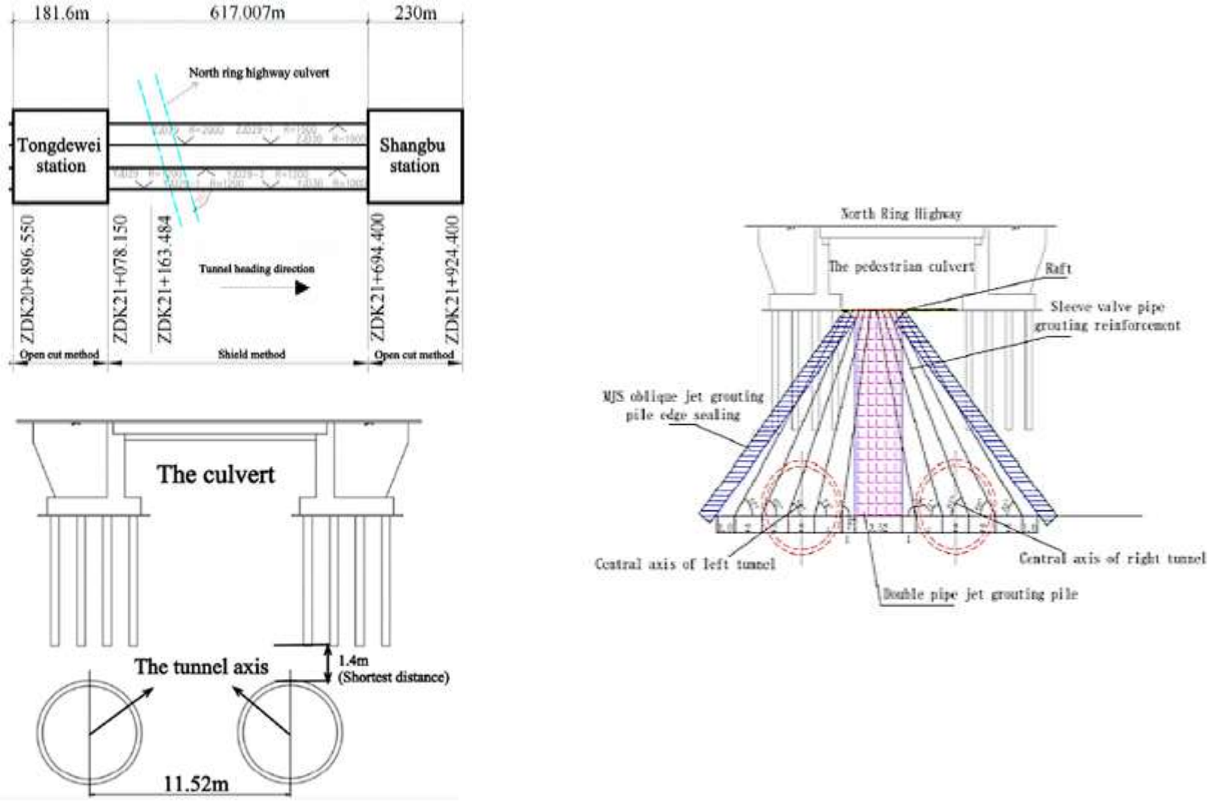
(Li et al., 2021) studied the Tongdewei Shangbu section of the Guangzhou Metro line when slurry-shield tunneling was constructed beneath the pedestrian culvert at the upper soft and lower hard composite strata, as illustrated in **Fig. 15 a and b**. Field monitoring and numerical simulation analysis were combined to regulate the inner stresses and use an inclined jet system to reduce segment, bridge, and culvert displacement. The deployment of an angled jet system could successfully control the concentrated release of stress that the shield tunneling project would create. With an angled jet system, the displacement of

the pile foundation in the under-passing project was decreased by more than 80%, with no additional bending moment applied to the pile foundation.
(AL-Malkee and Ahmed, 2021) investigated the effect of water-cement ratio on the physical and mechanical properties of soilcrete using sandy soil with different ranges of water-cement ratios ranging from 0.7:1 to 1.4:1. Their results showed that:
1. The relation of the water-cement ratio with uniaxial compressive strength (UCS) was an inverse linear one, i. e., a larger water-cement ratio was accompanied by a more significant drop in compressive strength,
2. The relation between the tangent modulus (E_{50}) and the uniaxial compressive strength is directly linear, and the higher tangent modulus was for the low water-cement ratio, and
3. The dry unit weight decreased with the increase in the water-cement ratio.

Another new development in the jet grouting system was done by **(Inazumi et al., 2021),** who focused on the middle-pressure jet grouting technique to improve the soil. They established a computer-aided engineering system (CAE). A comparative investigation was carried out with varying pressures to verify the existence of mechanical agitation and mixing and the effect of intermediate-pressure jet grout. The results were:

1- Using a reconstructive analysis of the results of an unconfined compression test on the soil, the mechanical properties of the ground model were found,
2- At the actual site, the final shape of the columnar soil improved was obtained and was relatively consistent with the design improvement diameter, and
3- CAE was an efficient tool for managing ground improvements' visual construction and maintenance.

Another development for jet grout technology was done by (Tran and Armediaz, 2021) based on an actual excavation site in Oslo, Norway. Two material models for jet-grouted retaining columns were compared. A new model named shotcrete (Concrete in Plaxis) was used, and the strain was divided into elastic, plastic, creep, and shrinkage strains. Mohr-Coulomb failure was used for the jetting material, and modified Cam Clay was used for soft soil because the Mohr-Coulomb is insufficient for the in situ soil.
(Huang et al., 2022) used post-grouting technology to recover the mechanical behavior of soils and improve various piles' bearing capacity. This may be considered a link between pile-bearing capacity and grouting parameters for a more rational and cost-effective design. Grouting slurry migration height was theoretically studied; the rising slurry was characterized by the motion of a Bingham fluid in an annular region. The study employed post-grouting technology on five board piles excavated after treatment. In this case, the model's calculated height was lower than the actual values entirely acceptable in engineering design.



(a) (b)

Figure 15. (a) Position of shield and cross-section. (b) Overall plan drawing of Reinforcement **(Li et al., 2021).**

The structure of landmarks is important for historical aspects. **(Severino et al., 2022)** discussed the deformation improvement by using jet grouting of such structures for a community. For example, the St. Nicholas Gate, a unique fortified design in Ukraine, or the local shear near the St. Andrews Church, and cracks in the wall due to landslides of the St. Illia Church. An analytical solution using RocScience Slide showed that the stability factors enhanced due to landslide prevention measures ranging from 1.21 to 1.37. By using jet grouting, the strength of soil-cement columns was strength was boosted from 1.6 to 4.0 times. This gave good proof for an efficient application of jet grouting to reduce the distortion of national landmarks. They recommended the use of this technology in other cities of the world.

4. CONCLUSIONS

Soil cement column is done by stabilization of soil with cementitious material using a jet grouting system. Jet grouting techniques are used for various soil types and ground conditions, which provides more freedom to how buildings are carried out on the chosen soil layer in various situations. Jet grouting is an ideal ground modification technique with an advantage over reinforcement and ground treatment. The operations of mixing, erosion, grouting, replacing, and filling occur at the same time. The physical and mechanical properties of soilcrete depend upon soil type, cement binders, and other operating parameters. Laboratory and field tests are recommended to evaluate the whole process.

Also, theoretical programs are recommended to carry out the entire design process. Thus, the following conclusions can be withdrawn:

1. Jet grouting techniques can be used mainly for all soil types,
2. The diameter of the soil cement column is greater in sandy soils than in clayey soils,
3. The diameter of the soil cement column from the double fluid system is larger than the single one,
4. The use of a quality control system with different types of jet grouting helps in controlling the whole system, whether it is a single, double, or triple system,
5. Sandy soils have good binding with water cement solution,
6. The compressive strength in different soils increases with time, and
7. The unconfined compressive strength grows in sandy and clayey soil but increases more in sandy soils.

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