International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING
ISSN:2147-6799 www.ijisae.org Original Research Paper

Some of The Field and Laboratory Studies on Grouting Properties for Weak Soils: A Review

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Submitted: 31/01/2023 **Accepted:** 04/04/2023

Abstract. Weak soils must be stabilized to meet technical specifications so that the constructions may be installed without massive settlements. Soil stabilization has become one of the most helpful options for this. In the 1970s and 1980s, admixture-based ground remediation developed in Japan. It is less compressible and has a lower permeability coefficient than the original soil after treatment. One of the oldest and most common ways to improve soil is to add admixtures of chemical materials such as cement, lime or/and quicklime, bitumen, and oil. Soil cement is a substance that is created by mixing cement with soil. In the mid-1970s, Sweden and Japan concurrently developed the conventional approach described as deep mixing. Cementitious or other materials are mixed into the soil in this in-situ treatment method. The deep mixing may inject using a jet grouting approach where erosion and mixing of weak soils in situ using a fluid jet. The injection strategies are a viable soil enhancement technique for fragile soils. Methods may use to safeguard piling structures. End-bearing pile repairs that used jet grouting required a robust and rigid framework to distribute the stresses of the grouted pile evenly. Since it can be applied to any soil, jet grouting is an excellent method for safeguarding pile foundations. The ground qualities may improve via chemical stabilization, which involves putting chemicals into the soil. Additives often used in asphalt mixtures include cement, lime, fly ash, and asphalt. Some of these are sodium silicates, acrylamides, N-methylolacrylamides, polyurethanes, epoxy resin, aminoplast, phenoplast, and lignosulfonate, the most common chemicals utilized in chemical manufacturing today. This study has presented field and laboratory analysis of the characteristics of the injection, and the results suggest an improvement before and after the injection. However, numerous elements must be considered for soil enhancement, including the aim, desired soil strength, toxicity, and rheology.

Keywords: *Injection, Chemical Materials Grouting, Field, Laboratory, Water- cement ratio, Groutability*

1. Introduction

The human population is growing exponentially, and fewer appropriate soils support the weight of buildings and structures. As a result of the shortage of land, the growth of wetland regions, mountain slopes, and landfills have become alternative locations for people to reside. Therefore, ground improvement has emerged as one of the most successful methods for treating the soil in such locations to get the necessary engineering characteristics and standards, allowing for installing structures without severe settling [1, 2, 3, 4, 5, 6, and 7]. Soil remediation is a strategy for enhancing the soil's geotechnical properties. Soil stabilizing strategies include vibration, surcharge load, structural reinforcement enhancement by structural fill, admixtures, grouting, and other approaches. Various strategies may be utilized for multiple reasons by boosting specific characteristics of soil conduct and enhancing the soil's stability and qualities [8, 9, 10, 11, and 12]. Reducing or eliminating water from the ground is a crucial element of ground treatment. Improving the ground's bearing capacity, decreasing total and differential settlement, and the time it takes for a settlement to occur are all significant aspects of ground treatment. Importing suitable fill materials to replace poor soil is the conventional method of improving the soil. Because of the expense of excavating, filling, and compacting geomaterial, this method is always expensive. To improve resistance to deformation, shear strength, provide cohesion and friction angle, or (more generally) to reduce conductivity and associated porosity in an aquifer, grouting is typically employed to plug holes in the earth (fissures and porous structures) [13, 14, 15, and 16]. The grouting conditioning technique is becoming more popular because it can increase the strength and stability of these discontinuous rock formations, which is essential in many engineering sectors, such as tunnels, dams, mines, bridges, and slopes [17 and 18]. After grouting augmentation, it has been discovered that improvements in the soil mass's bearing capacity are directly linked to the rheological qualities of the grouting materials (e.g., cement) [19].

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Meanwhile, the chemical grout's rheological qualities may significantly influence the radius of grout dispersion and the reinforcing impact [20 and 21]. This investigation aims to define the properties of various chemical grouts for enhancing soils, identify the type of grouting, and knowledge of chemical soil grouting materials. In addition, this study has presented field and laboratory analysis of the characteristics of the injection, and the results suggest an improvement before and after the injection. In addition to comparing grouting techniques, the optimal method for grouting in the field is determined based on the kind of soil.

2. Mixtures Remediation of soil

Between 1970 and 1980, the Japanese devised a method for ground improvement by mixing. Interjecting and blending Portland cement or another chemical stabilizer into the soil using revolving mixer jets, paddles, or shafts. Approaches such as soil mix walls, deep cement mixing, and the deeply blended approach are all examples of these techniques. Treating the soil increases its strength while decreasing its compressibility and lowering its hydraulic conductivity [22]. One of the oldest and most common ways to improve soil is to add blends such as cement, lime or/and quicklime, bitumen, and oil. Soil cement is a substance that is created by mixing cement with soil. A primary goal of admixture is to act as a synthetic cement, improving bearing capacity while decreasing the coefficient of permeability and compressibility. Face erosion of earth dams, levees, and channels may prevent by admixture-treated soil. Because this process requires specialized equipment to ensure full mixing, it has several drawbacks. Lack of proper mixing may result in alternating treated hard spots and untreated soft spots, which can be much more harmful than no treatment [23].

3. Injection and/or Grouting Methods

Initially, it should be made clear that grouting is not a particular additive. A fluidized substance is often injected under pressure as part of the grouting process to inject material into the ground. Grouting has decreased seepage by filling voids in its most basic form of open-graded or coarse soil (or rock cracks). Since many years ago, gravelly soil and rock fill dams have been filled with a slurry of fine-grained soils to increase their ability to hold water [24]. Ground engineering grouting may categorize as permeation grouting, compaction grouting, hydro-fracture grouting, jet grouting, rock grouting and compensation grouting, and deep mixing technique. Fig.1 depicts a drawing of ground engineering grouting styles.

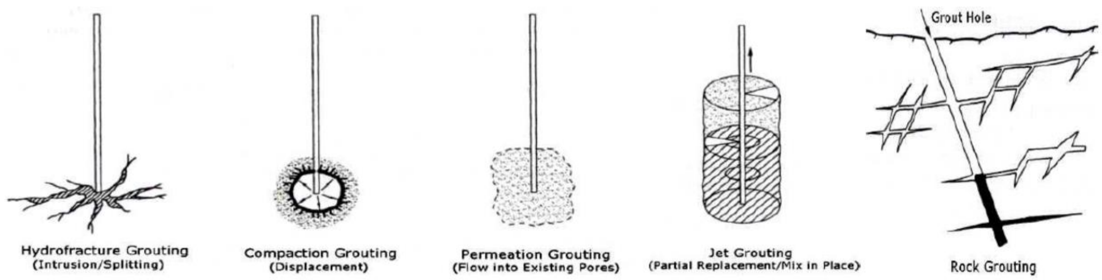

Figure-1 Grouting Engineering Styles of Grouting [25]

4. Deep soil mixing (DMM)

Most soft or loose soils may mix using the deep mixing method. Mechanical mixing is accomplished by drilling a hole into the soil and inserting a spinning mixing instrument. After that, the drilling rotation is reversed to extract the dry binder which is injected and mixed with the soil throughout the drilling process. As the binder and dirt are rotated together, a chemical reaction is immediately set in motion. The column share goes to the improved soil [27]. Between 0.5 and 1 m in diameter, the column may be up to 25 m long. Connecting the columns to form an in-situ wall or to support the whole structure is also possible. To enhance the shear strength of soft soils, dry mixing is an excellent option. Lime, cement, and additive quantities may alter to achieve different strength levels. Low moisture inorganic soils provide the best opportunity for improvement [28]. In the mid-1970s, DMM technique was advanced concurrently in Japan and Sweden (DMM). It is now widely accepted and valued that DMM is a method for repairing, improving, and providing assistance to the earth [26]. The DMM is unique because it is designed specifically for treating soft soils compared to similar ground improvement approaches. This method of treating the soil in situ uses various ingredients, including cementitious and non-cementitious, to create a cohesive mixture that can grout into place. Dry and wet deep mixing techniques are frequently categorized depending on the method of bleeding, the kind of binder, and the vertical area where mixing occurs [29]. Instead of a wet slurry, the former utilizes a powdered dry binder. Dry and wet executions need different equipment, as is obvious. However, the qualities of the treated soils are almost unchanged. As a result of the various design and application approaches, there are also varying installation patterns and the relative importance of different order factors [30]. The lime/cement column technique has been emphasized in the deep mixing strategy. The stimulating hydraulic conductivity simultaneously increases the soil's toughness and deformation properties. Pozzolanic reactions occur when binders like Portland cement, quicklime or/and lime, and other chemicals are combined with the ground in situ using rotating mixing machinery. In terms of long-term strength, certain of the employed binders gain the most from these procedures [31 and 33]. Cement-stabilized soil's cure time and its rising strength may extend by weeks or even months after blending because of the pozzolanic process [32].

5. Chemical Materials Injecting in Soil

Chemical stabilization is an efficient way of enhancing the soil's qualities by adding chemicals. It is common practice to add fly ash, lime, bituminous, and cement material. Additives such as this improve the soil's characteristics. Most chemical stabilization procedures rely on cementation and cation exchange reactions [34]. Chemical agents used in cementation include Portland cement, lime, fly ash, sodium silicate polyacrylamides, and bituminous emulsion. Sodium silicate and a gel-forming reagent are common ingredients in chemical grouts. Calcium chloride is used as a reagent in the Joosten technique for coarse-grained soils. Sodium aluminates, organic ester, and bicarbonates are all reagents. The gel duration, starting viscosity, and order of soil strength may all be influenced by varying the reagent and proportion used. While chemical grouts are injected as a solution, cementitious grouts are a mixture of finely ground particles in a fluid medium. Chemical grout may be used to fill areas with soil particles as small as 10 to 15 µm in diameter, whereas cementitious grout must be used for larger spaces. It has a higher penetration rate than cementitious grout, hence [35]. One-step and two-step chemical grouting methods are available. All chemicals are pre-blended before injection in a one-step procedure, and the system is designed so that the reaction takes place on-site. Using the two-step procedure, a first chemical is injected into the soil mass, followed by a second, which interacts with and stabilizes the soil mass. Chemical grouts come in a variety of forms, each with its own set of features and requirements. The most prevalent grouts are acrylate, sodium silicate, lignin, resin, and urethane [36].

5.1. Particulate chemical agents

Some of the most often used materials for grouting are slurry-form chemical agents such as lime or cement and lime or a blend of the two. Slag and fly ash were also used on occasion. It is common to generate particulate grout by mixing water with one or more particle materials, including but not limited to: fly ash, clay, or/and sand. A study by [37] found that the water-to-solids ratio significantly impacts the basic properties of particulate grout, such as strength, stability, rheology, durability, and fluidity. Table 1 included the most often used suspended grout ingredients, as well as their respective attributes, such as viscosity, water-to-binder ratio, toxicity, strength, and relative cost. Cement grouts often use water-to-cement ratios ranging from 0.5 to 4. It is more difficult to inject grout with lower w/c ratios because of its high viscosity. Stabilized cement grouts with low cohesion and high-pressure filtration resistance are often used in dam foundation grouting to achieve zero (or nearly zero) bleeding, low cohesion, and high-pressure filtration resistance [38]. Examples of common additives include Superplasticizers, which lower grout viscosity and prevent particle agglomeration. As a result, less water must use per unit of cement. Secondly, utilized at (1-4) percent by weight of water, hydrated bentonite (or sodium montmorillonite) stabilizes the grout, increases resistance to pressure filtration, and lowers viscosity. Thirdly, Category F fly ash, also known as silica fume, is a pozzolanic filler that is used up to 20% by dry weight of cement to enhance the longevity of the cured grout by making it more chemically resistant and to improve particle size distribution. Lastly, Welan gum, a high molecular weight biopolymer utilized as a thixotropic additive to improve resistance to pressure filtration and boost cohesiveness, is employed at roughly 0.1 percent by dry weight of cement.

Table-1 shows the most often used suspended grout ingredients, as well as their respective attributes, such as viscosity, water-to-binder ratio, toxicity, strength, and relative cost, modified from [39]

Description	Viscosity (cP) (water: binder ratio)	Toxicity	Strength	Relative Cost
		Particulate grout		
Type I cement	High (50 cPs) (2:1)	Low	High	Low

Type III cement	Medium (15 cPs) (2:1)	Low	High	Low
Ultra-fine cement	Low (8 cPs) (2:1)	Low	High	Medium

5.2. Chemical Grouts (Solutions)

Solutions grouts consist of water combined with two or more chemicals that might function as flocculants or stabilization components. Sodium sulfate, Sodium silicate formulations, ferrous sulfate, acrylates, phenoplasts, polyester, lignosulfonates, acrylamide, aminoplast, chromolignin, and any combination of two of these materials are a few of the well-known substances [41 and 43]. Also, there are several variables to consider when selecting a grout, including its viscosity, toxicity, setting time, the strength of a particular grout and the soil it is applied on, as well as its penetrability and water tightness [40]. In addition, grout distribution is essential to the development of grouting technology. Grouting requires careful consideration of grout hole equipment, the distance between boreholes, injection pass length, the number of grouting phases, grouting pressure, and pumping rate in the actual world [36]. Therefore, Table.2 gives directions for choosing silicate grout materials (cited by [42]).

Table-2 Classification according to toxicity, viscosity, and strength of selecting silicate grout materials [36]

silicate grout materials	**Toxicity**	**viscosity**	**strength**
Silicate			
Joosten process	Low	High	High
Siroc	Medium	Medium	Medium-High
Silicate –Bicarbonate	low	Medium	Low
Lignosulphates			
Terra Firma	High	Medium	Low
Blox- All	High	Medium	Low
Phenoplasts			
Terrier	Medium	Medium	Low
Geoseal	Medium	Medium	Low
Aminoplasts			
Herculox	Medium	Medium	High
Cyanaloc	Medium	Medium	High
Acrylamides			
AV-100	High	Low	Low
Rocagel BT	High	Low	Low
Nitti- SS	High	Low	Low
Polyacrylamides			
Injectite 80	Low	High	Low
Acrylate			
AC- 400	Low	Low	Low
Polyurethane			
CR-250	High	High	High

6. Some Reviewing Relevant Literature on the Properties of Grouting

The variety of grouts and the characteristics of each have been the subject of several in-depth scholarly works. Table.3 includes a summary of previous studies related to grout properties.

TABLE -3 Summary of previous studies related to grout properties

Name of Researcher	The description of the study
Zebovitz et al. [43]	Grouting permeation improves loose sand soil and mechanical rock properties and decreases permeability in ground improvement projects. Successful grouting requires the formation's predicted modifications. It was found that the profitability ratio is not a criterion that should be dependent on. Groutability values might be bigger or less than the limiting value of 25 and did not necessarily signal the success or failure of a given grouting process using particulate grout; several experimental declarations suggest that the grain size distribution and the relative density of fine sands can influence and regulate the grouting process.
Arenzana et al., [44]	The diameter of passing 10 percent of sand characteristics down to fifteen percent and a hydraulic radius as tiny as 0.002 mm could be grouted by suspensions of micro-fine cement with water: cement ratio of 4 or higher to give a successful injection with the stress of approximately (68.95 kPa) and soil penetration of at least 1.5 m. The grouted mass is stronger once the thick cement layer cures. Cement particles bind to sand grains. Some geotechnical specialists recommend thick grouting mixes (low water-to-cement ratio) and higher grouting stresses. However, preferred routes arise during injection, causing hydraulic fracture of the soil matrix or non-heterogeneity in the grouting of a soil structure.
Christopher et al. [45]	Variations in the grouted sand's grain size and grain size distribution substantially impact the mass's mechanical characteristics. Less relevant factors include the degree of water saturation and the effects of initial density.
Schwarz and Krizek [46]	Injecting micro-fine cement grouts affected rheological properties. A 1:1 grout needed almost 300 percent more pressure than a 2:1 grout, which required 35 percent more injection pressure than a 3:1 grout. The grouted sand required the maximum grouting pressure. The grout viscosity directly affects particle sedimentation and water buildup in grout-filled voids. Increasing the water-to-grout mix ratio increases soil injectability but decreases bleeding.
Lovely [47]	Need constant agitation of thin cement slurries. Add bentonite to the grouting mix to reduce the likelihood of bleeding cement grout. The benefit of bentonite is that it is a great cement grout mix anti-bleeder.
Huang and Airey [48]	Cementation contributes more to particle interlocking and friction at low densities than at high densities. A considerable portion of the cement fills the spaces at high densities without affecting inter-particle bonding. As soil density increases, a given cement amount becomes less efficient for sandy soil.
Glory et al. [49]	Grouting cement reinforces foundation beds. Cement grouting improves soil shear strength metrics (C) and (Ø). Grout's cement-to-water ratio controls strength on sandy soils. Various investigations on improving sandy soil bearing capacity by grouting cement indicate that cement grouting may increase soil tolerance (bearing capacity), especially in cohesionless soils.
Markou and Atmatzidis's [50]	Findings that the grouting either has little impact on the angle of internal friction of sands or results in an increase of up to 4^{o}. Significant indications indicate that cementitious, pulverized fly ash may be used successfully to provide a permeation grouting for coarse sand.

Name of Researcher	The description of the study
Akbulut and Saglamer [51]	Utilizing a 3 percent superplasticizer in the grout mix made it easier to grout into soil samples and increased soil strength compared to cement-grouted (additive-free) samples. The granular structure was subjected to the effects of cement grout, which added adhesive forces at each point of contact to the mechanical forces derived from the external stresses.
Miller and Roycroft [52]	Discovered that compaction grouting is a very efficient technique for preventing the liquefaction of sensitive soils. Grouting has the greatest effect on sandy soil. However, silty soil also improved, but in a less significant manner.
Ibragimov [53]	Raising the cement's milling fineness or removing or lowering the cement's coarse fraction might increase the cement's permeability. An increase in milling fineness, a decrease in grout separation, the creation of a more uniform and stable density structure, an increase in the strength of the cement stone, and a decrease in the rate and volume of water may have improved several elements of the cement grout.
Haeri et al. [54]	Revealed that Portland cement-cemented soils had the maximum shear strength at low cement concentration and grout confining pressures. When confining stress increases, Portland cement-cemented soil has lower shear strength than gypsum-cemented soil. It exceeds lime-cemented soil shear strength. As confining stress grows, Portland cement-cemented soils' shear strength becomes less. Portland cement always outperforms gypsum and lime when the cement concentration exceeds 4.5 percent.
Ribay et al. [55]	Micro fine cement grout is ideal for long-term soil stabilization due to its high creep limit strengths. Because of its low creep strength, silicate grout, on the other hand, can be used as a temporary treatment.
Yilmaz et al. [56]	Used a soil grout mixture dubbed "Soil Crete" to avoid liquefaction at Jackson Lake Dam and Wickiup Dam in the United States. Jet grouting was used to achieve the deep soil mixing that formed Cretan soil. Field experiments demonstrated that jet grouting was effective and that the strength achieved was adequate to make it a viable design choice in terms of time and cost.
Ibragimov [57]	Demonstrated soil-cement composition and strength may be anticipated throughout the building process when using jet grouting on pile foundations. Production parameters can be adjusted to ensure the design strength of the soil cement; the amount of soil, cement, and water in the pile's design volume can be determined; the pile's soil cement strength can be predicted; and the layer of deposits of unexposed soils, whose properties may influence the parameters of the grouted pile, can be permanently fixed.
Liu et al. [58]	In laboratory experiments, grout flow patterns are power-law when W/C = 0.5 and Bingham when W/C = 0.7. The other three Newtonian fluids (W/C = 1.0, 1.5, 2.0) have similar rheological curve slopes and magnitudes. The fundamental water-cement ratio is 0.7 for power-law fluid and 1.0 for Bingham fluid and Newtonian fluid. Cement grouts with different water-to-cement ratios react differently to temperature. Temperature increases cement grout shear force. However, high water-to-cement ratios diminish grout as the temperature rises.
Zhu et al. [59]	Compared soil grouting using cement-sodium silicate slurry and cement slurry in a laboratory experiment: First, the grouting pressure rises slowly for both slurries; after 4 minutes, the cement-sodium silicate slurry's pressure rises rapidly while the cement slurry's pressure remains relatively steady. Cement-sodium silicate grouting pressure rises with viscosity. Second, cement-sodium silicate grouts better than cement slurry, although it decreases as the beginning pressure rises. Soil composition may cause this. Finally, laboratory-tested cement-sodium silicate slurry sets faster in the soil during practice grouting.

Name of Researcher	The description of the study
Liu and Sun [60]	Studied hydro-mechanical coupling during grouting in cracked media. The in-situ stress and interference between multiple grouting holes affect fracture geometry and the grouting process, which may be exploited to optimize grouting hole arrangement and increase reinforcing effects.
Liu et al. [61]	Suggested a stronger composite grouting material. Thus, grouting material that lowers seepage may not strengthen geology and geotechnics. Shear and seepage testing should be done before industrializing grouting material. For strength, choose grouting material carefully.

7. Some of the Previous Studies Concerning Grouted Piles in the Field

Field investigations using grouted piles were summarized in Table.4.

Table-4 Summary some of the field investigations using grouted piles

Name of Researcher	the description of the study
Almer E.C. van der Stoel [62]	Researched three grouting methods to increase pile foundation bearing capability (permeation, compaction, and jet). Results from grouting with silica gel and micro cement were: • Permeation grouting may increase pile-bearing capacity and stiffness. • Compaction grouting heaved soil and piles (caused by the large volumes of grout injected). The compaction ratio may increase load-bearing capacity. • When jet grouting below pile toe level for foundation rehabilitation, pile displacements increased fast. The grouted concrete piles exhibited deformations that were almost elastic and showed no indication of approaching their ultimate bearing capacity.
Fu and Zhou [63]	Compared grouting piles and regular piles by using four piles (two of them are typically bored cast in-situ piles with lengths of (29.4, 24.4 m) and (14.4 m), respectively. In fine sand soil, one of the other two was pressure grouted only beneath its tip with a length of (14.4 m), and the last one with 14m grouted from its sides and tip; their diameters were (0.92, 0.88, 0.88, 0.87 m). Perforated pipes were utilized to grout the two piles with slurry (water: cement: clay), 0.6: 1: 0.025, at 1 MPa for 1.6 m^3. Without grouting, 29.4m and 24.4m piles had 6,650 and 6,100 kN ultimate bearing capacities, respectively. With grouting, 14.4m and 14m pile lengths were 9500 and 10450, respectively.

Name of Researcher	the description of the study
Rollins K.M. et al. [64]	The impact of jet grouting on increasing lateral pile group resistance using field testing. They used seven piles of jet grout columns with a 1.22 m diameter to a depth of 3.76 m and found that jet grouting with 400 kg/m3 of cement (20 percent by weight) increased the average compressive strength of soft clay from 40 to 60 kPa. Starting stiffness has risen by 400% and lateral resistance by 1950 kN, or 155%. Passive pressure and side/base shear on the jet grout mass caused 75% of the increased resistance, whereas the piles and reinforced soil caused 25%.
Wang et al. [65]	Shanghai's soft soil responses to horizontal twin-jet grouting. Five horizontal jet-grouted columns were used in the field test, and the pressure of the pore water, the lateral earth pressure, the subsurface soil displacements, and the ground surface heave were all measured. According to the data collected, the amount of extra pore-water pressure was more than four to six times the undrained shear strength of the soils. The most significant lateral displacements and ground surface heave were just 80 and 17 millimeters, respectively. There was a 15-20 times increase in the impact radius of jet-grouted columns.
Nguyen K.T. et al. [66]	Investigated pile bottom post grouting technique to strengthen the bearing capacity of bored piles under gravel soil layer in Vietnam with the in-situ grouting method. The pile's bearing capacity rose 1.67 to 1.75 times after grouting.

8. Conclusions

Dependent on the literature review, the following inferences might be obtained:

1- The grouting is performed using deep mixing, injection, or jet grouting techniques, using cement and chemicals as the components. Due to its limited penetrability, cement grout is ideal for coarse-grained soils, while chemical grout is suitable for fine-grained and coarse-grained soils.

2- Because there aren't many places to develop in cities, stabilizing the soil has become one of the most critical steps in getting the land ready for construction without significant settling.

3- The DMM is the only technology created exclusively to treat soft soils compared to comparable procedures for improving the ground. The primary benefit of these processes is an increase in durability, particularly for some of the applied compounds.

4- Chemical remediation is an efficient approach to enhancing ground quality by incorporating chemicals.

5- Substances such as acrylamide, polyurethane epoxy resins, sodium silicate, N-methylolacrylamide, aminoplast, lignosulfonates, and phenoplasts are used often. The selection of a certain chemical for ground improvement will rely on various parameters, including the purpose, required toxicity, soil strength, and rheology.

6- Post-grouting technology in this project saves money, improves construction quality, and increases dependability.

References

[1] Manfred R. Hausmann. 1990." Engineering Principles of Ground Modification". McGraw-Hill, Inc., U. S. A., ISBN 0 07 027279 4. pp: 346-402.

[2] Reuben H. Karol, 2003." Chemical Grouting and Soil Stabilization (3rd edition)". Marcel Dekker, Inc., U. S. A., ISBN 0 8247 4065 3. pp: 113-133.

[3] Rahil, F.H., (2007), "Improvement of Soft Clay Underneath a Railway Track Model Using Stone Columns Technique." Ph.D. Thesis, University of Technology, Iraq.

[4] Fattah, Mohammad Y., Mohammad M. Al-Ani, and Mahmoud TA Al-Lamy. "Studying collapse potential of gypseous soil treated by grouting." Soils and Foundations 54.3 (2014): 396-404.

[5] Al - Sarrajy, S.A., (2016), " Study of Grouted Pile Models in Sandy Soil." M.Sc. Thesis, University of Technology, Iraq.

[6] Al -Kabee, H.N., (2018), "Improvement of Soft Clay by Hearing Technique." M.Sc. Thesis, University of Technology, Iraq.

[7] Al - Gharbawi, A.S. (2021), " Behavior of Carbonated Collapsible Gypseous Soil Admixtured with Reactive Product" Ph.D. thesis, Building and Construction Engineering Department University of Technology, Baghdad, Iraq

[8] Vinson T (1970). "The Application of Polyurethane Formed Plastics in Soil Grouting", Univ. Calif., Berkeley, CAL.

[9] Cambefort, H., 1977. "The Principles and Applications of Grouting". Q. J. Eng. Geol., Vol. 10, pp: 57-95.

[10] Edil TB (2003). "Recent advances in geotechnical characterization and construction over peat and organic soils" Proceedings 2nd International Conference on Advances in Soft Soil Engineering and Technology. (Eds). Huat et al. Malaysia: Putrajaya, pp. 3-25.

[11] Moseley MP (2000). "Ground Improvement" CRC Press, Inc ISBN 0 7514 0073 4.

[12] Keller (2009). Keller Geotechnical Construction, "Ground improvement Technique", Retrieved on 12 Sept 2009 at www.haywardbaker.com.

[13] Karol RH, and Dekker M (1983). "Chemical Grouting" USA: New York and Basel Inc.

[14] Nonveiller E (1989). "Grouting Theory and Practice", Elsevier Science Publication Company, Inc., New York, US.

[15] Moseley MP, and Kirsch K (2004). "Ground Improvement", 2nd edition Spon Press in an imprint of Taylor and Francis group, U. K.

[16] Nikbakhtan, Babak, and Morteza Osanloo (2009). "Effect of grout pressure and grout flow on soil physical and mechanical properties in jet grouting operations." International Journal of Rock Mechanics and Mining Sciences 46.3: 498-505.

[17] Hassler, Lars, Ulf Hakansson, and Hakan Stille (1992). "Computer-simulated flow of grouts in jointed rock." Tunneling and Underground Space Technology 7.4: 441-446.

[18] Tian, Maolin, Lijun Han, and Qingbin Meng (2020). "Experimental study on the mechanical performance of grouted specimen with composite ultrafine cement grouts." KSCE Journal of Civil Engineering 24.1: 38-48.

[19] Varol, Ahmet, and Süleyman Dalgıç (2006). "Grouting applications in the Istanbul metro, Turkey." Tunneling and Underground Space Technology 21.6: 602-612.

[20] Magill D, and Berry R (2006). "Comparison of Chemical Grout Properties" Avanti International and Rembco Geotechnical Contractors.

[21] Axelsson, Magnus, and Gunnar Gustafson (2006). "A robust method to determine the shear strength of cement-based injection grouts in the field." Tunnelling and underground space technology 21.5: 499-503.

[22] Raison, Chris A., ed (2004). Ground and soil improvement. Thomas Telford.

[23] Ingles, O. G., and Metcalf, J. B. (1973). Soil Stabilization: Principles and Practice, John Wiley & Sons, Inc., New York, NY.

[24] Han, Jie (2015). Principles and practice of ground improvement. John Wiley & Sons.

[25] CIRIA, 2000. "Grouting for grouting engineering". CRIRIA press, London, U. K., ISBN 0 86017 514 6. pp: 17-22.

[26] Mitchell JM, and Jardine FM (2002). "A guide to ground treatment" CIRIA C573, ISBN 0 86017 5731.

[27] Kazemian S (2009). "Assessment and Comparison of Grouting and Injection Methods in Geotechnical Engineering", Eur. J. Sci. Res. ISSN 1450-216X, 27(2): 234-247.

[28] Hashim R, Islam S (2008b). "Stabilized Peat by Deep Mixing Method: A Critical Review of the State of Practice" the Electronic J. Geotech. Eng., 13.

[29] Bruce DA (2000). "An Introduction in Deep soil Mixing Method as uses in Geotechnical application" US department Transportation Federal Highway Administration.

[30] Bromes BB, Holm G, Bredenberg H (1999). "Dry Mix Method for Deep Soil stabilization", Balkema Rotterdam, ISBN 90 5809 108 2.

[31] Anagnostopoulos CA, Chatziangelou M (2008). "Compressive Strength of Cement Stabilized Soils, a New Statistical Model", The Electron. J. Geotech. Eng., 13, Bund. B.

[32] Bergado, D.T., 1996. "Soil compaction and soil stabilization by admixtures". Proceeding of the

Seminar on Ground Improvement application to Indonesian Soft Soils. Indonesia: Jakarta, pp: 23-26.

[33] Hashim R, Islam S (2008a). "Properties of stabilized peat by soil cement column method" Electron. J. Geotech. Eng., 13, Bund. H. Ingles.

[34] Mitchell JK (1993). "Fundamental of soil behavior", John Wiley and Sons, New York.

[35] US Army Corps of Engineers (1995). "Chemical Grouting", Manual No. 1110-1-3500, Washington, DC, USA.

[36] Shroff AV, Shah DL (1999). "Grouting Technology in Tunnelling and Dam Construction", (2nd edition), A.A Balkema Publishers.

[37] Littlejohn, G.S. (1982), "Design of cement base grouts", Proceedings of the Conference on Grouting in Geotechnical Engineering, New Orleans, Louisiana, U.S.A., February.

[38] Nicholson P. G. 2015 "Soil improvement and ground modification methods" Elsevier Inc. page 12.

[39] Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J.G., and Berg, R.R. (2006). "Ground Improvement Methods". FHWA NHI-06-020, Federal Highway Administration, Washington, DC.

[40] Rawlings CG, Hellawell EE, Kilkenny WM (2000). "Grouting for ground engineering", CIRIA C 514, ISBN 0 86017 514 6.

[41] Saeed, Y. M., Al-Obaidi, S. M., Al-hasany, E. G., and Rad, F. N. (2020). Evaluation of a new bond-type anchorage system with expansive grout for a single FRP rod. Construction and Building Materials, 261, 120004.

[42] Sina, K., and Maassoumeh, B. (2012). Review of soft soils stabilization by grouting and injection methods with different chemical binders. Scientific Research and Essays, 7(24), 2104-2111

[43] Zebovitz, S., Krizek, R. J. and Atmatzidis, D. K. (1989): "Injection of fine sands with very fine cement grout". Journal of Geotechnical Engineering, ASCE, 115 (12), 1717- 1733.

[44] Arenzana, L., Krizek, R. J., and Pepper, S. F. (1989): "Injection of thdilute microfine cement suspensions fine sands". 12 Int. Conf. on Soil Mechanics and Foundation Engineering, Brazil, 18/2, 131-1334.

[45] Christopher, B.R., Gill, S.A., Giroud, J-P., Juran, I., Schlosser, F., Mitchell, J.K. and Dunnicliff, J. (1989): "Reinforced soil structures, volume design and construction guidelines", Report No. Fhwa-Rd-89-043, 287 pp.

[46] Schwarz, L. G., and Krizek, R. J. (1994): "Effect of preparation technique on permeability and strength of cement-grouted sand". Geotechnical Testing Journal, ASTM, 17 (4), 434–443.

[47] Lovely, K. M. (1998): "A study on the properties of grouting and control of permeability of grouted media", Ph.D thesis School of Eng. Cochin University of Science and Technology, Kochi.

[48] Huang, J. T., and Airey, D. W. (1998): "Properties of artificially cemented carbonate sand". Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 124 (6), 492–499.

[49] Glory. J., Abraham, B. M., Jose, B. T., and Paul, B. (2001): Improvement of bearing capacity of sandy soils by grouting", IGC 2001, The New Millennium Conference 14- 16 Dec, 2001 Indore (MP).

[50] Markou, I. N. and Atmatzidis, D. K. (2002): "Properties and performance of a pulverized fly ash grout". Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 128, No. 8 682-691.

[51] Akbulut, S., and Saglamer, A. (2002). Estimating the groutability of granular soils: a new approach. Tunnelling and underground space technology, 17(4), 371-380.

[52] Miller, E. A. and Roycroft, G. a. (2004): "Compaction grouting test program for liquefaction control". Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 130 (4), 355–361.

[53] Ibragimov, M. N. (2005). Soil stabilization with cement grouts. Soil mechanics and foundation engineering, 42(2), 67-72.

[54] Haeri, S. M., Hamidi, A., Hosseini, S. M., Asghari, E., & Toll, D. G. (2006). Effect of cement type on the mechanical behavior of a gravely sand. Geotechnical & Geological Engineering, 24, 335-360.

[55] Ribay, E. D., Maigre, I. D., Cabrillac, R. and Gouvenot, D. (2006): "Factors affecting the creep behavior of grouted sand". Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 132 (4), 488–500.

[56] Yilmaz. D., Babuccu. F., Batmaz. S. and Kavruk. F. (2008): "Liquefaction analysis and soil improvement in Beydag dam". Journal of

Geotechnical and Geological Engineering, 26: 211-224.

[57] Ibragimov, M. N. (2013). Characteristics of Soil Grouting by Hydro-Jet Technology. Soil mechanics & foundation engineering, 50(5).

[58] Liu, Q., Lei, G., Peng, X., Lu, C., & Wei, L. (2018). Rheological characteristics of cement grout and its effect on mechanical properties of a rock fracture. Rock Mechanics and Rock Engineering, 51, 613-625.

[59] Zhu, M., Zhang, Q., Zhang, X., and Hui, B. (2018). Comparative study of soil grouting with cement slurry and cement-sodium silicate slurry. Advances in materials science and engineering, 2018.

[60] Liu, Q., and Sun, L. (2019). Simulation of coupled hydro-mechanical interactions during grouting process in fractured media based on the combined finite-discrete element method. Tunnelling and Underground Space Technology, 84, 472-486.

[61] Liu, J. Q., Yuen, K. V., Chen, W. Z., & Zhou, X. S. (2020). Grouting for water and mud inrush control in weathered granite tunnel: A case study. Engineering Geology, 279, 105896.

[62] Almer E.C. van der Stoel in (2001) "Grouting for pile foundation improvement", Delft University Press, Netherlands, ISBN 90-407- 2223-4.

[63] Fu, X., & Zhou, Z. (2003). Study on bearing capacity of bored cast-in-situ piles by post pressure grouting. In Grouting and ground treatment (pp. 707-715).

[64] Rollins K.M., Adsero M.E. and Brown D.A. (2008) "Use of jet grouting to increase lateral pile group resistance in soft" The 14th World Conference on Earthquake Engineering, Beijing, China.

[65] Wang, Z. F., Shen, S. L., Ho, C. E., & Kim, Y. H. (2013). Investigation of field-installation effects of horizontal twin-jet grouting in Shanghai soft soil deposits. Canadian Geotechnical Journal, 50(3), 288-297.

[66] Nguyen Khanh Tung, Wu Li, Nguyen Minh Thanh, and Nguyen Xuan Loi (2015) "Application of Pile Bottom Post-Grouting Technology to Increase the Bearing Capacity of Bored Piles in Vietnam" report on case-study in Vietnam. ejge.