Journal of Water Resources and Geosciences
Vol. 2, No. 2, 2023

Brief History and Fundamentals about the Grouting

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Abstract:

One of the most utilized techniques for preventing water leaks in fill dam structures is grouting which modifies the soil properties to increase the endurance, reduce compressibility, and reduces the hydraulically conductive of the original soil. This research focuses on grouting and its effect on improving the structure of dams. In order to construct the projects without experiencing significant settlement, it is necessary to stabilize weak soils to meet technical requirements. Grouting is one of the best solutions for this purpose that has emerged recently is rock/soil stabilization. To support the weight conveyed via the infrastructure, the engineers were compelled to modify the soil's properties. The important issues of grouting can be assigned from the complicated geological circumstances and the interactions between the grout and the fragmented rock mass, the geological and geotechnical characteristics of the rock or soil to be grouted which regarded significant factors affecting the grouting's design and present a significant challenge to the analysis of the grouting diffusion mechanism. For better engineering qualities, a variety of grouting procedures involve injecting dry or wet materials into the ground. Increasing strength or decreasing permeability within the treated bulk of ground are common goals. Conceptually, the simplest method involves introducing a fluid grout into the pore spaces, allowing it to set, and then delivering the necessary qualities. The properties of the grouting materials were analyzed in the field and lab for this study, and the findings point to an improvement both before and after the injection. The goal, intended soil strength, toxicity, and rheology are just a few of the many factors that must be considered for rock/soil improvement.

Keywords: Dam, Grouting, Soil, Structure.

تاريخ موجز وأساسيات حول الحشو

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الخلاصة

إحدى التقنيات الأكثر استخدامًا لمنع تسرب المياه في هياكل السدود هي الحشو الذي يعدل خصائص التربة لزيادة القدرة على التحمل، وتقليل الانضغاطية، ويقلل من التوصيل الهيدروليكي للتربة الأصلية. يركز هذا البحث على الحشو وأثره في تحسين بنية السدود. من أجل بناء المشاريع دون التعرض لتسوية كبيرة، من الضروري تثبيت التربة الضعيفة لتلبية المتطلبات الفنية. يعد الحشو أحد أفضل الحلول لهذا الغرض والذي ظهر مؤخرًا وهو تثبيت الصخور والتربة. ولدعم الوزن المنقول عبر البنية التحتية، اضطر المهندسون إلى تعديل خصائص التربة. يمكن تحديد القضايا المهمة المتعلقة بالحشو من خلال الظروف الجيولوجية المعقدة والتفاعلات بين الجص والكتلة الصخرية المجزأة، والخصائص الجيولوجية والجيوتقنية للصخور أو التربة المراد حشوها والتي تعتبر عوامل مهمة تؤثر على تصميم الحشو وتمثل أهمية كبيرة. تحدي لتحليل آلية نشر الحشو. للحصول على خصائص هندسية أفضل، تتضمن مجموعة متنوعة من إجراءات الحشو حقن المواد الجافة أو الرطبة في الأرض. تعد زيادة القوة أو تقليل النفاذية داخل الجزء الأكبر من الأرض المعالجة من الأهداف الشائعة. من الناحية النظرية، فإن أبسط طريقة تتضمن إدخال الجص السائل في المسام، مما يسمح له بالثبات، ثم توفير الصفات اللازمة. تم تحليل خصائص مواد الحشو ميدانياً ومختبرياً لهذه الدراسة، وتشير النتائج إلى تحسن قبل وبعد الحقن. إن الهدف، وقوة التربة المقصودة، والسمية، والريولوجيا ليست سوى عدد قليل من العوامل العديدة التي يجب أخذها في الاعتبار لتحسين الصخور/التربة.

الكلمات المفتاحية: السد، الحشو، التربة، الهيكل.

1. Introduction

In order to comply with safety rules, a growing number of dams need to be repaired and modified to improve the stability. Reducing the foundation's uplift pressure of concrete dams as a crucial safety precaution to avoid dam failure by sliding or overturning also the uplift pressure can be decreased by installing drainage or building a grout curtain. Both approaches are currently used regularly and are widely seen as enhancing one another. Dam safety may be seriously impacted over time if the grout curtain deteriorates and the installed drains become clogged. Re-grouting the foundation or increasing drainage capacity are two strategies that can be used to make dams more stable against sliding and flipping (Spross et al., 2016). Drains and grout curtains may have a temporary reduction in the uplift pressure because it may leading to a rise in overall pressure or a decrease in safety against uplift pressure (Meshkabadi & Zandi, 2019). In recent years, grouting technology has developed into a geotechnical engineering discipline that focuses primarily on strengthening or impermeable foundation treatment for dams and other structures. It has also become a key tool for structural dam rehabilitation (Bidasaria, 2004). Important factors impacting the grouting design include the geotechnical and geological characteristics of the rock and/ or soil that will be grouted (Alkaya & YeşIl, 2011) because they play a crucial role in the success or failure the structures (Al-Auqadi ,et al., 2023). In 1802 for the French port of Dieppe, Charles Berigny is credited with employing grout injection to stabilize civil structures for the first time which helped in Grouting innovations occurred on both sides of the English Channel after Portland Cement's patenting in 1824 (Lees, 2018). Grout is predominantly a fluid form of concrete which applied to fill gaps and the most common ingredients in grout are water, cement, and sand (Shinde, et al., 2008). Despite recent significant improvements in the grouting of medium to fine materials, the grouting of coarse materials still has a number of unknowns issues (Heidarzadeh ,et al., 2013) because the coarse materials sometimes not cohesive or doesn’t fill the voids perfectly (Lagerlund, 2009). The dams' reinforcing grouting is currently not subject to any exact specifications (Yu ,et al., 2022) due to the different geological conditions of the areas where dams are built (Aghda, et al., 2019). An optimization computation was used to select the grouting technology. Leakages that start within weeks or months can be a sign of dam damage. Because of this, it's important to keep a constant eye on the dam and secure it as necessary. Remediation using a grouting slurry of appropriate material composition is one potential strategy to stop dam leaking (Park & Oh, 2018). The important components of remediating embankment dams are selecting the right application technology and material composition. Cost, mixture stabilization, the material's ease of entry into caves, and fissures are important considerations when choosing an acceptable material composition. Above all else, a material's fineness is a crucial physical property (Kociánová & Drochytka, 2016) because the grouting flow qualities in a fresh state as well as the mechanical behavior in a hardened state are greatly influenced by the features of particles size (Xu, et al., 2020). The creation of mixtures, which must subsequently be evaluated in both their fresh and hardened states, comes after the selection of suitable raw materials. An analysis of each test's results informs the selection of the mixture's ideal composition for a particular type of dam. The mixture is administered using the right machinery and equipment, considering the dam's surroundings and a geological assessment, as well as the local conditions (Kociánová & Drochytka, 2016).

The most frequent technique for reinforcing and repairing broken concrete dams, as well as the elimination of seepages, is grouting. Grouting is applied to stop the deterioration process, for example, by keeping water from entering, and, if possible, to raise the dam's structural safety level. Always keep in mind that simply grouting over cracks won't stop them from forming in the first place. Always considering the structural characteristics of the cracks and assuring a higher lifetime for the rehabilitation, this repair method may (in many situations) be used in conjunction with other forms of reinforcement or repair schemes that remove or minimize the cause(s) of cracking. Despite the fact that other types of polymers, like epoxy resins and polyurethanes, are occasionally seen as better suitable for these tasks, cement-based compounds have been used successfully to inject fractures and contraction joints in concrete dams (Ricardo et al., 2019). Grout injection is a difficult step even though grouting is a common procedure primarily used for treating soil in addition to filling cracks and spaces in concrete constructions (da Rocha Gomes ,et al., 2023).

Because grouting techniques have advanced significantly in recent years, an updated review on this topic is indispensable. The variety of grouting applications are highly affected by the state of the geological and geotechnical criteria. There are many engineering aspects that grouting can be used to solve different problems. Depending on the specific application, grouting can be used alone, in combination with other technologies and methods, or as the primary or only way to improve a property.

This study will focus on the purpose of grouting and the ways by which it can be achieved, in addition to highlights the relevant grouts to provide useful information about the materials and application fields to understand how different components and surrounding circumstances affect the overall procedures.

2. Brief history of grouting

In the field of preventing disasters and reducing flooding, dams are a crucial component. But dams have a lengthy history, and over many years, they have been elevated and developed. Traditional techniques for dam fortification and antiseepage include grouting (Wang et al., 2020) which began about few centuries ago as the brilliant idea of a Frenchman Berigny (Kalkani, 1991) and was put into practice using incredibly crude methods. It was gradually improved and its use spread to become a typical approach in the civil engineering structures. Modern grouting methods were unquestionably created in the early 20th century. It was viewed for a very long time as a form of art that could not be improved upon or studied scientifically. In contrast, a small number of specialized enterprises in France, Switzerland, and Italy made significant contributions to the development and advancement of grouting methods, means, and equipment at a time when its performance was mostly a privilege and a well-guarded secret (Nonveiller, 1989).

Goals that were partially attained may be seen throughout the history of dam foundation grouting in the United States, which started with a project in New York in the late nineteenth century. Additionally, it contains problematic practices that seem all too familiar to modern grouting professionals as well as novel processes and smart concepts, only few of which were put into practice (Weaver, 2003). The USACE National Inventory of Dams estimates that there are roughly 84,000 dams in the country. Nearly 50% of these have a Significant or High Hazard rating and are older than 50 (Stare, et al., 2012).

Compared to the history of civil engineering, which began on the cusp of human civilization, grouting has only been around for about 200 years. The French civil engineer Charles Berigny, who enrolled in the Ecole Polytechnique in 1794, was the creator of the injection technique. He was in charge of managing the harbor of Dieppe in 1802, where water had eaten the soil beneath the flimsy foundation of the tide sluices built on gravelly material, endangering the stability of the structures with strong undercurrents. The thought to fix the damages by grouting came to him as a true inspiration in order to overcome impossibly difficult technical challenges. First, Berigny fixed the foundation's wooden sheet piles. The bottom of the sluice was then punctured with holes spaced at 1 m intervals. He used what he dubbed a "blow pump" to inject plastic clay through the holes, as seen in Figure 1. It was made up of an 8 cm ID wooden cylinder that he filled with plastic clay and then topped with a wooden piston. Heavy hammer blows onto the piston forced the clay into the hole, and the process was repeated until the clay filled the spaces between the foundation slab and the earth. Pozzolanic mortar was used in the same way to fill any gaps between the foundation slab and the earth.

After World War II, the Dinaric Karst in Yugoslavia, an area with complex geological conditions and highly permeable karstified limestone formations, began to develop its hydropower potential. A key factor in this growth was grouting. The success or failure of significant initiatives for the development of hydroelectric power at the time hinged on finding the optimal solution, which was a professional challenge (Nonveiller, 1989).

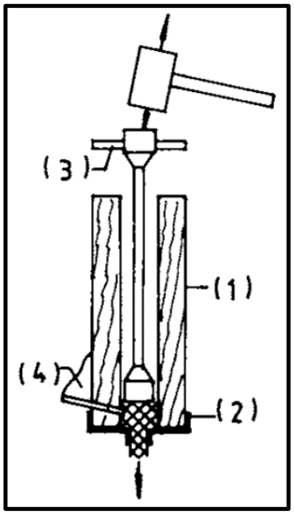

Figure (1): Shows the Berigny injection "blow pump" with its (1) wooden cylinder, (2) fitting for connecting with the hole, (3) piston from wood, and (4) hole and plug for preventing vacuum when the piston is drawn out (Nonveiller, 1989).

3. Purposes of Grouting

Grouting is the technique of applying pressure to the injection of liquids, mixed suspensions, or semi-solid mixes to obtain one or more desired final results in terms of enhancing engineering qualities (Fu et al., 2019). Usually, the grout injection must gel or harden within the treatment zone for this to occur. High-mobility grouts (HMGs) are injected during the permeation grouting process into minuscule areas within soil or rock masses, minuscule spaces between these materials and an existing structure, and/or minuscule cracks or fractures inside structures themselves. Void-filling grouting involves using low-mobility grout (or grouting) (LMG) or other materials with properties appropriate for effectively filling large voids (Moos, 1984). Compaction grouting is a well-known mechanical in situ procedure that includes injecting stiff soil-cement grout under strong pressure to push out the surrounding soil (Jafarzadeh & Garakani, 2013). The process of "compaction grouting" involves injecting plastic, semi-solid mixtures into materials to densify or eliminate deformable ones. Specialized methods like jet grouting or hydrofracture grouting are used for in-situ modification or replacement. The engineering qualities that can be enhanced by grouting are discussed in the paragraphs that follow. Grouting can be used in conjunction with other technologies and procedures or as the main or only method of improving a property, depending on the particular application (Moos, 1984).

3.1. Permeability reduction by grouting. The grouting is frequently applied to lower hydrostatic forces acting on structures, lower seepage or leakage rates through or into new or existing structures and foundations, change flow gradients or flow paths to achieve specific design objectives, prevent internal erosion of foundation and embankment materials, and/or control water for excavations as necessary to facilitate dewatering or excavation stability (Moos, 1984). In any essential hydraulic application, grouting is often one of several lines of defense (Kayabasi & Gokceoglu, 2019).

3.2. Mechanical properties enhancement as a result of grouting. The mechanical properties of soil or rock foundation materials can be improved by grouting for the purpose of sustaining structures or excavations (Deng et al., 2020). By grouting, qualities such as bearing capacity, settlement-related parameters like elastic modulus and void ratio, shear strength, and the elimination of voids that might negatively affect loading conditions or the response to loads can all be improved. Grouting can also be used as a settlement tool to prevent or repair structural damage (Moos, 1984).

4. Typical grouting applications

Grouting is applied to give the base of structures and buildings more strength which can be summarize as the following subsections (Moos, 1984):

4.1. Dams and Lock Structures. For new or old earth and concrete dams, as well as lock structures, grouting is frequently used in the following ways:

(1) Hydraulic barrier grouting to regulate seepage and pressure distributions (also known as grout curtain construction).
(2) Using grout for foundation consolidation will lessen foundation and building deflections under load.
(3) Contact grouting at the foundation-to-structure interface.
(4) Filling voids in building foundations.
(5) Jet grouting to replace loose-material zones or compaction grouting to densify loose deposits.
(6) Pre-treating foundations made of fractured rock in order to construct cutoff walls.
(7) Grouting of joints or fissures in constructions that leak.
(8) Backfilling or abandonment of instrument and exploratory holes.
(9) Zones must be improved as necessary to help with dewatering and/or excavation stability.

4.2. Tunnels. Grouting is frequently used for tunnel work in the following ways:

(1) Before tunneling, to lessen water inflows during construction.
(2) Pre-tunnelling grouting to increase the stability of the excavation and/or lessen or prevent ground loss.
(3) Installing grout between the lining of the tunnel and the surfaces of the tunnel excavation to lower the loads of long-term tunnel, enhance stress distributions, and lower water inflows.
(4) Repair grouting of joints and gaps to stop leaks.

(5) During tunneling, compensation grouting is used to counteract settlement and to safeguard structures that might suffer from ground loss.

4.3.Other Grouting Applications.

(1) Grouting for rock and soil anchors to increase anchor capacity and offer corrosion protection.
(2) Displacement grouting techniques for lifting structures.
(3) Filling abandoned subsurface structures, such as pipes.
(4) Annular space grouting for re-lined pipes.
(5) Application of environment.
(6) Fill in the gaps in the mine.

5. Decision on choosing the grout

Numerous grout features, including toxicity, setting time, rheology, the strength of the grout and grouted soil, stability or permanence of the grout and grouted soil, and the penetrability and water tightness of the grouted soil, should be taken into consideration when choosing a grout type. Additionally, the advancement of grouting technology depends heavily on grout spreading. In the real world, the grouting process necessitates careful consideration of the grout hole apparatus, spacing between boreholes, duration of injection passes, quantity of grouting phases, grouting pressure, and pumping rate. Table 1 provides guidance for choosing the grouts in this manner (Sina Kazemain, 2012).

Table (1): Ranking of grouting based on strength, viscosity, and toxicity (Sina Kazemain, 2012).

No.	Grouts	Strength	Viscosity	Toxicity
1	**PU**			
	CR-250	High	High	High
2	**Acrylate**			
	AC- 400	Low	Low	Low
3	**PAMs**			
	Injectite 80	Low	High	Low
4	**Acrylic amides**			
	AV-100	Low	Low	High
	Rocagel BT	Low	Low	High
	Nitti- SS	Low	Low	High

5	**Aminoplasts**			
	Herculox	High	Medium	Medium
	Cyanaloc	High	Medium	Medium
6	**Phenoplasts**			
	Terramier	Low	Medium	Medium
	Geoseal	Low	Medium	Medium
7	**Lignosulphates**			
	Terra Firma	Low	Medium	High
	Blox- All	Low	Medium	High
8	**Silicate**			
	Joosten process	High	High	Low
	Siroc	Medium- High	Medium	Medium
	Silicate –Bicarbonate	Low	Medium	Low

6. Injection and/or Grouting Methods

The first grouting methods were developed for soil remediation and enhancement. At the time, the major objective was to increase the soil's carrying capacity and stability by hardening it and reducing its permeability. Today's grouts have a wide range of uses, and the grouting methods vary according to the kind of grout, how it functions, and the application. The composition of the grout, the site's geology, the environment, the reason for grouting, the kinds of fractures, the project's budget, and the time frame for completion will all have an impact on the grouting technique selection (Mercedes, 2023).

Prior to anything else, it must be made clear that grouting is not a specific additive. Every so often, a fluidized liquid is injected under pressure into the ground as part of the grouting procedure. Grouting has decreased seepage by obstructing spaces in the most fundamental types of coarse or open-graded soil (or rock fissures). For many years, rock-fill dams and gravelly soil dams have had a slurry of fine-grained soils injected to enhance their ability to store water. Various forms of grout are used in ground engineering, including permeation grout, compaction grout, hydro-fracture grout, jet grout, rock grout, compensation grout, and deep mixing technique (Shareef et al., 2023). Drawings of several ground engineering grouting designs are shown in Figure (2).

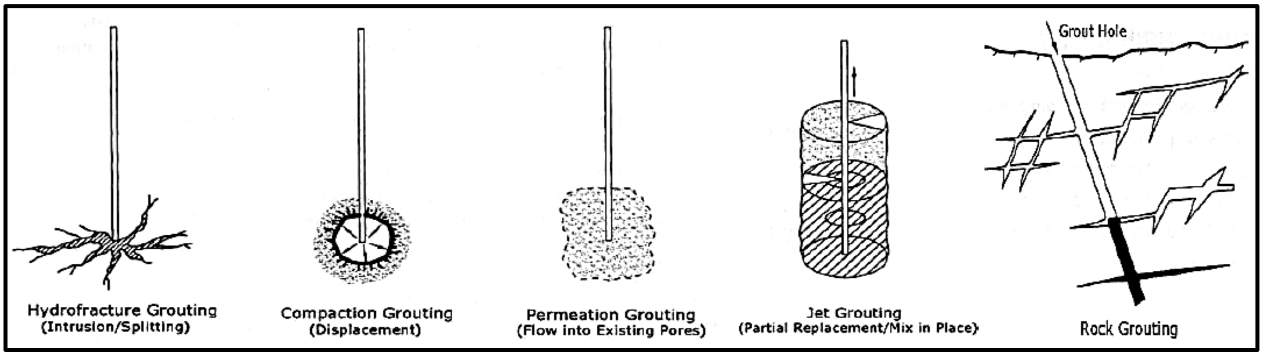

Figure (2): Various Grouting Styles for Grouting Engineering (Kazemian & Huat, 2009).

7. Subsurface Investigation

Problematic soils are widespread and extensively distributed, especially in arid or semi-arid regions of the world (Obead & Fattah, 2022). To ascertain whether unfavorable circumstances exist that can be addressed by grouting, a subsurface examination similar to that often performed for foundation design objectives is usually sufficient. If any of the following are found throughout the course of these studies, grouting should be considered as a treatment option if it potentially impairs the project's success: rocks that are easily dissolved or show signs of solution activity, noticeable open joints, broken or heavily jointed rock, faulting, losses in circulation or drill rod drops while drilling, or peculiar groundwater conditions. To plan the grouting program, specific information on subsurface conditions is required. Information on the attitude, orientation, and spacing of joints or joint openings, including the type of filler used if any, the rock types boundaries, faults locations and broken regions, the depth to sound rock, and the location of the water table must be available in order to determine the scope and estimate the costs of drilling and grouting operations in rock. In particular, the television camera or borehole camera can be helpful in gathering this data. It will be necessary to know the soil's stratification, density, grain size, and permeability if it is going to be grouted. Additional explorations (trenches, borings, etc.) should be carried out to gather the information that is lacking if it cannot be found either from the rock that was discovered during the first site excavation or via the design investigations. the important tests which should be taken into account can be listed as the following (BASHAM et al., 2004):

7.1 Field tests

7.1.1. Pressure tests. If the injection of grout that forms gels is being explored, pressure testing that uses measured amounts of water at known pressures into exploratory boreholes serves a valuable purpose. The results of the pressure tests will demonstrate whether or not the soil or rock mass is permeable to water or other fluids of a similar viscosity. An effective method for determining the permeability of uniformly porous, water-bearing soil layers is a pumping test. It is rarely worthwhile to pressurize test rock to see if it will accept cement or clay grout. If pressure testing is performed for this purpose, each tested increment of the borehole should be studied using a borehole camera or television to assess the size of the apertures that are expected to accept water.

7.1.2 Test grouting. It is the most reliable way to get accurate answers to questions concerning a rock's ability to withstand a grout that contains suspended particulates. The test-grout program would be made to offer details on the rock's groutability, the ideal mixtures, and probable grout volumes if the rock takes grout. Even though test grouting is recommended for the stated purpose, it is rarely believed to be essential if just cement grouting of rock is involved. According to cumulative experience from dozens of job sites where cement grouting was carried out in a wide range of subsurface settings, Injection of cement grout is permitted; if certain circumstances are identified during preconstruction examinations. Exploratory trenches and pits are very helpful for estimating costs and efficacy when testing soils with chemical grout. It might be possible to make significant financial savings by testing representative sections on huge works. By experimenting with various grouting procedures, it is feasible to establish the optimal hole spacing, pressure, injection rate, and setting time for any meaningful combination of factors.

7.2 Laboratory tests

7.2.1. Permeability. In general, laboratory permeabilities are lower than field permeabilities estimated from field pumping testing due to the difference between lab and field circumstances.

7.2.2 Gradation. For instance, Field permeability values have been associated with the effective grain size of Mississippi River alluvial sands (D10 size).

7.2.3 Density. In order to perform calculations and assess the stability and permeability characteristic of the in-place soil mass, calculations should be made on the density and void ratio of undisturbed specimens.

7.2.4 Chemical tests. Groundwater samples should be chemically analyzed to look for substances like $CaSO_4$, $MgSO_4$, $NaSO_4$, organic or mineral acids, and alkalies that could harm chemical grouts or cement. It is also important to check the water's pH.

8. Grouting Mixture and Categories

Numerous cracks and holes will weaken the rock mass and increase its permeability, which will affect the stability and security of the dam's foundations. In areas with challenging geological characteristics, several high dams are built (Bondarchuk, 2012). Filling joints and fissures in the rock mass with grout is a typical and efficient way to enhance the geological conditions of dam foundations. This will reduce seepage, increase bearing capacity, and improve deformation resistance. Fracture grouting is still a challenging problem because of the convoluted fracture distribution, intricate fluid-structure interaction effects, and lack of grout knowledge diffusion behavior and associated fracture deformation. The grouting process must be studied well with a technique that takes into account the fluid-structure interaction in order to uncover the grouting mechanisms in the cracked rock mass (Zhu et al., 2019).

The grouting mixes are classified into four categories: unstable or stable suspension, pure solutions (non-evolutional), colloidal solutions (evolutional), and gaseous emulsions (expanding mixes that significantly increase in volume), depending on the rheological behavior that determines the mixture's applicability. The right mix of design and pumping is crucial. Also crucial is that the injection must solidify before any sedimentation takes place (Kociánová et al., 2015).

The type of soil and the distribution of the soil's particle sizes determine the operational limits of certain grout mixes (Chaitanya et al., 2023). Four different types of grout mix exist. These are:

(1) Pastes and mortals, like cement, are used to patch up holes and fissures.
(2) Suspensions to strengthen and seal joints and sand, such as ultra-fine cement.
(3) Solutions like water glass (silicate).
(4) Emulsions, including chemical grout.

The grouting may be categorized as follows:

(1) Rock or fissure grouting.
(2) Compaction grouting.
(3) Jet grouting.
(4) Penetration grouting
(5) Vacuum grouting
(6) Fracture grouting.

8.1 Components of grouting mixture

8.1.1 Cement

A mortar, cement may thicken and harden when combined with water in both air and water. It primarily functions as a superb hydraulic mortar with exceptional hydraulicity and strength. For permeation grouting, ordinary Portland cement is most frequently employed. Raw materials including calcium (CaO), silicon (SiO_2), aluminum (Al_2O_3), and iron (Fe_2O_3) oxides are required for the manufacture of the Portland cements main phases. CaO is found in limestone, while SiO_2, Al_2O_3, and Fe_2O_3 are found in clay. Depending on their composition, marls contain varied proportions of all four oxides (Christodoulou, Lokkas, Droudakis, et al., 2021).

8.1.2 Suspensions

The suspensions consist of water and particles with grains larger than 0.1 microns. They can be used to strengthen soil formations and minimize permeability, and they are the most cost-effective option when compared to the grouts described in the other categories. The suspensions become significantly more viscous during the curing process, and it can take several hours to several days for them to reach a desirable level of strength. They typically display rheological behavior similar to that of Bingham. These grouts include pure Portland cement, pozzolans-cement, suspensions of clay and bentonite, bentonite-cement mixes, and fine-grained cement (Christodoulou, Lokkas, Markou, et al., 2021).

8.1.3 Solutions

The solutions are produced by the dissolution of appropriate chemical compounds in water, and they can be classified as True Solutions or Colloidal Solutions based on the type of chemical compound employed to generate them. The actual solutions contain solids that have molecules too big to be mechanically separated from water. When grouting materials hardens, which can take anywhere between a few seconds and an hour, they exhibit a very low viscosity that holds steady up until that point. This category includes resins. The resins act like Newtonian fluids, range in viscosity from 2 to 10 cP, and typically experience severe shrinkage, which lowers their strength. Resins come in a variety of varieties. A few of them, such as phenol plastics, amino plastics, polymers (foam materials), and polymethyl acrylates (PMAs), are still in use, although acrylamides and lignosulfonates have not been utilized in applications recently due to their toxicity. Granules of solids larger than molecules but smaller than the solids in grouts (0.001µm d 0.1µm) are what define colloids. The admixtures are used to determine how viscous they are. The viscosity starts out low and steadily rises throughout the hardening process, which can take anywhere from a few minutes to a few hours. The main component of silicate solutions in the modern world is sodium silicate, which must be dissolved in water with either an inorganic (sodium aluminate) or an organic (esters) hardener. With a composition of 50–60% sodium silicate, 8–10% hardener, and 30–42% water, a typical silicate solution behaves like a Newtonian fluid and has a viscosity between 10 and 200 cP. These solutions' strength varies depending on the hardener type and silicon content (greater content enhances strength). These grouting materials are often employed solely to lessen the permeability of soil formations because they do not generally have high strengths (Christodoulou, Lokkas, Markou, et al., 2021).

8.1.4 Emulsions

In order to solve soil stability and waterproofing issues, the most widely used emulsions are asphalt, an asphalt mixture, soap, and casein in water, as well as asphalt with an appropriate filler like clay in water (Christodoulou, Lokkas, Droudakis, et al., 2021).

8.2 The grouting categorized (Chaitanya, et al., 2023)

8.2.1 Penetration grouting. It is also known as "permeation grouting" (Figure 3), a technique for grouting where the soil's pores and seams are filled with grout without affecting the soil's volume or structure. Therefore, it permeates granular and coarse soils, resulting in the formation of a cemented mass. When utilizing this grouting method, the selection of binders is mostly based on the soil's permeability. Other names for it include cement grouting and pressure grouting.

When the permeability coefficient exceeds (10-20) cm/sec, water-cement mixes are used; when it is less than (10-5) cm/sec, costly resin-based grouts are used. Soils having K values lower than (10-6) cm/sec are frequently incapable of being grouted using the permeation method.

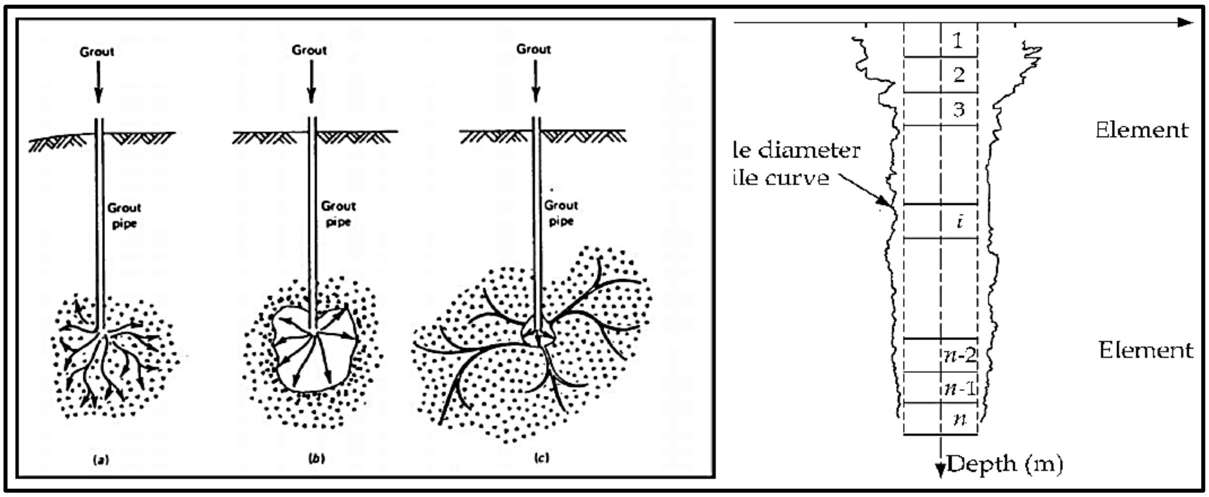

Figure (3): Penetration grouting (Chaitanya et al., 2023).

8.2.2 Vacuum grouting. Vacuum grouting is a technique that allows grout to be "sucked" into a void even though grout is generally propelled by pressure (Figure 4).

Figure (4): Vacuum grouting (Chaitanya et al., 2023).

8.2.3 Compaction grouting. In this sort of grouting, the soil mass is injected under pressure with a thick consistency of soil-cement grout, which consolidates and subsequently stabilizes nearby soils. The grouting mixture is created in a way that prevents it from mixing with the soil or filling in soil voids. The soil it is injected into is instead moved (Figure 5).

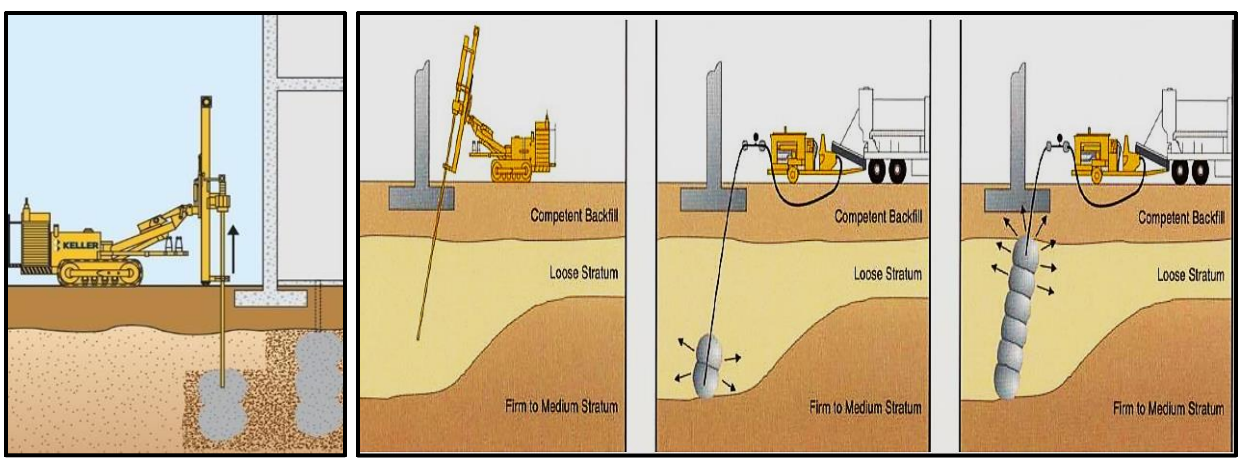

Figure (5): Compaction grouting (Chaitanya ,et al., 2023).

8.2.4 Jet grouting. For this kind of grouting, high-velocity fluid jets are used to physically disturb the soil. The soil is improved during the eroding and mixing of grout with the dirt. It costs more than permeation grouting. Single, double, and triple jet systems are the three types of jet grouting systems (Figure 6).

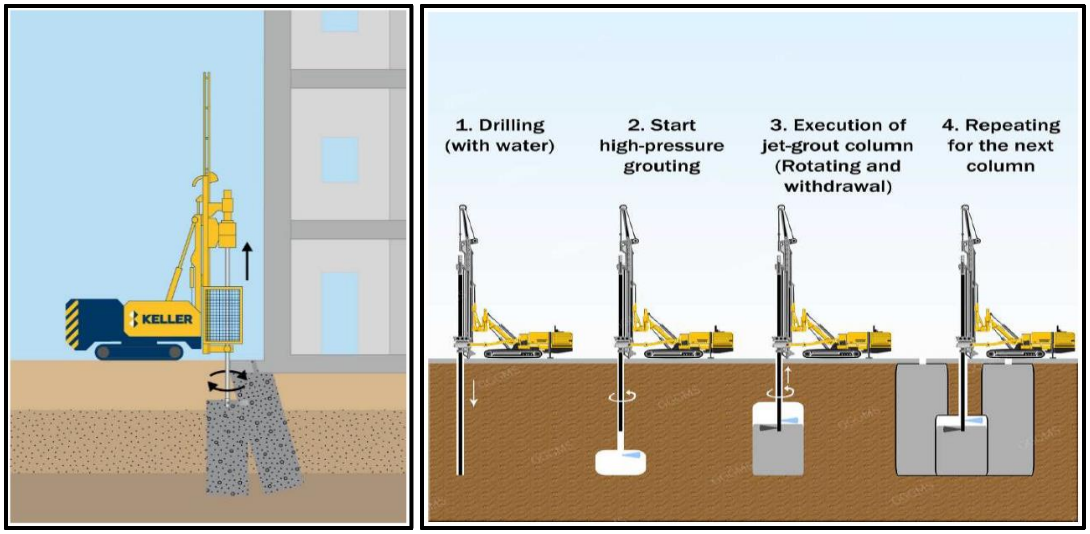

Figure (6): Jet grouting (Chaitanya, et al., 2023).

8.2.5 Fracture grouting. It is commonly referred to as compensation grouting (Figure 7). In order to create thin lenses or roots inside the soil mass, a cement slurry grout is pumped into the soil at high pressure. The compacted soil is raised above the surrounding soil by the roots-like lenses. It significantly raises the soil mass's density and macroscopic strength.

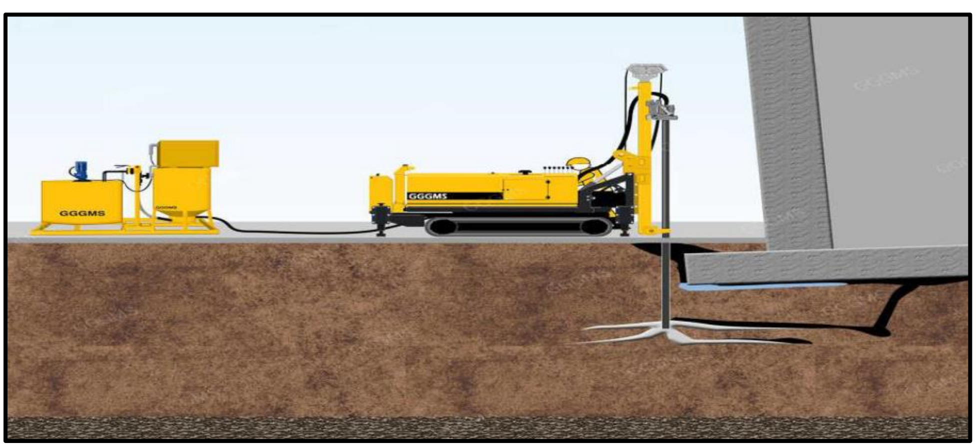

Figure (7): Fracture grouting (Chaitanya et al., 2023).

8.2.6 Fissure or rock grouting. Rock grouting, illustrated in Figure 8, is the practice of employing grout injection to entirely or partially fill fractures, fissures, or joints in a rock mass without enlarging existing cracks or creating new ones. Drilling a hole in the rock mass and injecting grout through it under pressure is the treatment method. This type of grouting is frequently employed in fissured rock to prevent water from flowing along the joints.

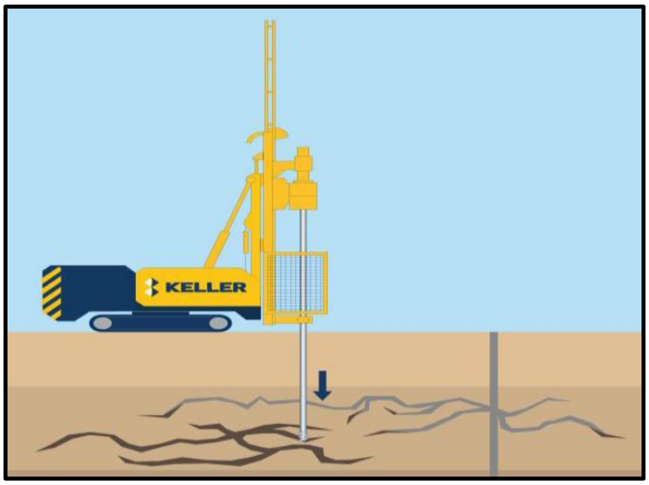

Figure (8): Rock grouting (Chaitanya et al., 2023).

9. Grouting procedures

Regardless of the number of exploratory borings or other preconstruction surveys, knowledge of the continuity and size of groutable natural openings in the rock beneath the surface will be comparatively scant before grouting operations begin and only marginally better once grouting is finished. It is possible to determine the existence of groutable voids before grouting and to confirm their existence after grouting, but it will be entirely speculative as to how big, how they look, and what they mean. The "art" of grouting is mostly concerned with how to address these comparatively unidentified subterranean problems successfully without being able to see them. The descriptions of grouting procedures are meant to help the apprentice, not to take the place of experience (Fell et al., 2014). For grouting rock, all of the techniques and methods described apply. Some of them work just as well for grouting with other materials, as seen in the following points (BASHAM et al., 2004):

9.1 Curtain Grouting. The purpose of curtain grouting is to develop a hydraulic barrier that lessens water seepage beneath a dam's base (Fan, et al., 2016). By drilling and grouting a series of holes in a straight line, curtain grouting creates a grouted curtain or barrier. Its goal is to lessen permeability. Any shape or attitude is possible for the curtain. It can circle a shaft or other deep excavation, cross a valley as a vertical or inclined seepage cutoff beneath a dam, or be almost horizontal to create an umbrella of grout over an underground facility. A grout curtain might consist of just one row of holes or it can include 2 or more parallel rows (BASHAM et al., 2004).

9.2 Blanket or Area Grouting. To achieve a better affinity of curtain grouting, consolidation grouting for fill type dams (blanket grouting) is used, which reduces the porosity of the dam foundation surface to extend the permeable route (Kikuchi et al., 1998). In the blanket grouting, the permeability of cracked or leached rock is reduced or improved by injecting grout into shallow holes drilled in a grid pattern. Consolidation grouting is another name for this type of grouting. Before curtain grouting deeper zones at greater pressures, blanket grouting can be applied to create a grout cap. It can also be applied to consolidate damaged or cracked rock surrounding a tunnel or other underground structure (BASHAM et al., 2004).

9.3 Contact Grouting. The filling of gaps between an underground excavation's walls and its built-up liner is known as contact grouting. These gaps could be caused by concrete shrinking, excavation overbreak, or liner misfitting the excavation wall. Contact grouting is frequently done at the tunnel's crown (BASHAM et al., 2004).

9.4 Mine and Cavity Filling. The techniques for installing embedded grouting accessories and the grouting technology allowed for grout filling of the joints and cavities in the dam (Argal & Ermoshin, 1984). To mitigate or prevent roof collapse and subsidence, grout can be used to fill massive natural holes beneath engineered constructions or abandoned mines. If seepage control is in place, the apertures size allows the use of a grout comprising sand or small gravel and sand. In order to fully seal the smaller voids, a second (or third) phase of grouting is perhaps necessary, with the grout's coarser elements left out. If available, mine maps should be used to cut down on the number of holes number required to inject the grout. Use observation holes to examine the grout dispersion from various injection positions. Drilling in a grid pattern can be used to provide coverage if mine maps are unavailable and it is impossible to identify the size and direction of haulage ways and room spacings. Bulkheads of thick grout must be built in all mine tunnels that cross the perimeter of the area if the mine workings go beyond the boundaries of the area that needs to be treated in order to stop grout from spreading further than it can be used. If sufficiently free from debris and muck, large solution cavities, like mines, can be grouted using coarse grout. Prior to backfilling with concrete or grout, it might be essential to enable access to the cavities and manually clean them because grout is unlikely to displace a significant quantity of solution-channel filling. If the treatment's primary goal is seepage control, cleaning is very crucial (BASHAM et al., 2004).

9.5 Order of Drilling and Grouting. For grouting curtains, holes are originally drilled on rather large spacings, typically between 20 and 40 feet. Prior to drilling any intermediate holes, these holes—known as main holes—are grouted. By dividing the spaces between adjacent holes, intermediate holes can be found; the first intermediates are halfway between main holes, and the second intermediates are halfway between the first and second intermediate holes. This method of dividing the spaces between the holes is continued until the grout consumption reveals that the rock is sufficiently tight. Every hole of an intermediate set in any area of the grout curtain is grouted before drilling the following set of intermediates. Although initial holes are frequently drilled on 20-foot centers, other spacings are acceptable. If grout consistently breaks from one primary hole to the next, the primary spacing needs to be increased. Based on previous experience under similar conditions, it may be acceptable to have a final spacing of between 5 and 10 feet. However, it is important to select a primary spacing of 30 feet as it will decrease to 7.5 feet with the second set of intermediates. The split spacing strategy reduces the distances between grout holes, which should result in a decrease in the average grout consumption per linear foot of the hole. If the final spacings in a grout curtain constructed in rock that has no substantial voids are 5 ft or less, the total grout taken for neat Portland-cement grout is probably going to average less than 0.5 cu ft of cement per linear foot of the hole. It is a good idea to arrange your operations while grouting a wide area that will serve as a building's foundation so that the final grouting is carried out through intermediate holes that are drilled between rows of already grouted holes in each segment. Since grout can only go so far in the final holes, the greatest amount of pressure can be used to seal all openings. Prior to doing any more grouting, it should be thought about creating a barrier to prevent grout from traveling through the region to be consolidated if there are no existing natural barriers. This barrier could be created by grouting a row of holes around the area's perimeter. To act as the capping zone for deeper grouting, the blanket grouted area must be suitably tightened by grouting in order to avoid noticeable penetration via the 20 higher-pressure grout holes that must be injected into lower horizons. The type and position of the groutable openings in the rock, the orientation of the grout holes, and the grouting processes will all affect how far apart everything will ultimately be spaced. In general, the spacing between the holes must be closer to the more groutable openings there are. In severely fragmented rock, holes spaced 2 or 3 feet apart might be needed (BASHAM et al., 2004).

9.6 Inclined Grout Holes. The greatest number of joints that can be intersected while drilling holes in jointed rock should be done so (Kawasaki et al., 1998). Directional drilling might be necessary for this. Vertical grout holes will be perfect if every joint dips at an angle of less than 45 degrees. Instead, grouting must be done at spacings of a few inches if joints and holes are vertical or nearly vertical in order to get the same level of coverage as is attainable with suitably slanted holes spaced at 5-ft intervals. Because higher inclinations raise drilling costs and cancel out the savings from fewer holes and wider spacings, holes are often not inclined above 30 degrees from the vertical in practice. The joint that is closest to normal to the grout curtain has the smallest seepage path across it. Therefore, if the pattern of jointing is at all advantageous, it is best to build a grout curtain to prevent seepage using inclined grout holes that are inclined along the plane of the curtain. This allows for the most joint intersections that are normal to the curtain. If the curtain requires more than one line of incline grout holes, spacing the holes across consecutive rows will improve the coverage of joints running normally to it. If the joints intersect the curtain diagonally, holes shouldn't be spaced apart (BASHAM et al., 2004).

9.7 Drill Water Loss. During drilling operations, it is possible to learn a lot about the rock the drill is hitting by keeping an eye on the drill water. The cuts that the water carries include information about the type and color of the rock. Changes in the volume of water returning can be used to calculate the permeability of a rock. Usually, a sudden change in the amount of water that rises to the surface indicates the presence of a permeable horizon. If permitted to flow, all drill water and cuttings created there will be transported into this permeable zone. If drilling proceeds, there is a possibility that the opening will get so clogged with cuttings that the drill water cannot pass and will once more vent from the hole top. In this manner, holes of significant size can be filled by grouting but still pose a risk for seepage because there is no assurance that water seeping through the rock won't wash away the pipe's cuts. To avoid clogging big groutable apertures with cuttings, drilling should be stopped once all the water has been lost and the hole grouted. If there is a rapid, obvious increase in water, drilling is frequently stopped, and the hole is grouted. This is done rather than risking cluttering the permeable zone with cuttings because it allows for the individual treatment of a groutable void of a significant size. The same justification would be sufficient for grouting after a quick water loss if the risk of clogging with cuttings did not exist. If the drill rods do not drop to indicate a cavity at the location of water loss or gain, it might be preferable to advance the hole by one or two feet prior to grouting. By doing this, the hole will be well inside the permeable zone. Within a foot after the initial water loss, a subsequent one has frequently happened. More drilling in these circumstances might have prevented a cycle of drilling and grouting. Grouting may be required if rapid losses of about half the drill water occur, or if accumulated losses equal roughly half of the water being pushed into the hole. Use your best judgment when deciding whether an apparent water gain or loss is valid. If the water source for the drill also supports other activities, pressure differences could lead to volume changes in the drill water that are easily mistaken for losses or gains. One could interpret a full loss of drill water as a collar of cuttings around the drill pipe or a clogged bit that stops return water from flowing. As the hole gets deeper in porous rock, the water loss may progressively get worse. Drilling operations cannot be stopped to grout if the pores are too small to accommodate the grout (BASHA, et al., 2004).

10. Conclusion

In this review paper, various kinds of grouting have been covered. According to the research studies have been presented in this review, fixing weak soils to make them suitable for development using ground improvement techniques is both technically possible and beneficial from an economic standpoint. Various soil types, including loose sand, silt, clay, and weak rocks, have been stabilized using the mentioned procedures of grouting widely. The following factors need to be taken into account while creating a technique for ground improvement. Proper knowledge, comprehension, painstaking attention, and intuitive perception are necessary for having an effective grouting procedure. By carrying out a suitable injection program, it is possible to immediately improve the characteristics and mechanical behavior of soil formations. The injection strategy may:

(1) Be completed as a part of the preliminary fieldwork before the start of a project's construction.
(2) Participate in the main project's construction.
(3) Be planned and carried out as a "treatment" when unanticipated events occur while a project is being built.

Finally, compared to the original soil, the treated soil is less compressible, stronger, and has lower hydraulic conductivity.

References

Aghda, S. M. F., GanjaliPour, K., & Esmaeilzadeh, M. ,2019, The Effect of Geological Factors on the Grout Curtain Performance Analysis of Darian Dam Using the Results of Instrumentation Data in the First Impounding. *Journal of the Geological Society of India*, *93*(3). https://doi.org/10.1007/s12594-019-1185-x

Al-Auqadi, R. S., Al-Jawadi, A. S., & Al-Naqib, S. Q. ,2023, Petrographic and Geotechnical Aspects of the River Terraces at the University of Mosul as Buildings Foundations. *Iraqi Geological Journal*, *56*(1). https://doi.org/10.46717/igj.56.1C.19ms-2023-3-30

Alkaya, D., & YeşIl, B. ,2011, Grouting applications of grout curtains in Cindere dam and hydroelectric power plant. *Scientific Research and Essays*, *6*(19), 4039–4047. https://doi.org/10.5897/sre11.103

Argal, E. S., & Ermoshin, V. M. ,1984, Sealing the joints of the Andizhan concrete dam. *Hydrotechnical Construction*, *18*(5). https://doi.org/10.1007/BF01428823

BASHAM, D. L., WRIGHT, J. W., FERGUSON, K. I., & MOY, G. W. ,2004, *UNIFIED FACILITIES CRITERIA (UFC) GROUTING METHODS AND EQUIPMENT* (Issue January).

Bidasaria, M. (2004). *Scholars ' Mine Grouting Technology for Rehabilitation of Tillar Earthen Dam*. 0–7.

Bondarchuk, A. ,2012, *Rock mass behavior under hydropower embankment dams with focus on fracture erosion and rock mass stability (Doctoral dissertation)*.

Chaitanya, J. S. N., Divya, K., & Rao, K. B. ,2023, a Review on Grouting Technique. *International Research Journal of Modernization in Engineering Technology and Science*, *02*, 698–702. https://doi.org/10.56726/irjmets33505

Christodoulou, D., Lokkas, P., Droudakis, A., Spiliotis, X., Kasiteropoulou, D., & Alamanis, N. ,2021, The Development of Practice in Permeation Grouting by using Fine-grained Cement Suspensions. *Asian Journal of Engineering and Technology*, *9*(6), 92–101. https://doi.org/10.24203/ajet.v9i6.6846

Christodoulou, D., Lokkas, P., Markou, I., Droudakis, A., Chouliaras, I., & Alamanis, N. ,2021, Principles and Developments in Soil Grouting: a Historical Review. *WSEAS TRANSACTIONS ON ADVANCES in ENGINEERING EDUCATION*, *18*(c), 175–191. https://doi.org/10.37394/232010.2021.18.18

da Rocha Gomes, S., Ferrara, L., Sánchez, L., & Moreno, M. S. ,2023, A comprehensive review of cementitious grouts: Composition, properties, requirements and advanced performance. *Construction and Building Materials*, *375*. https://doi.org/10.1016/j.conbuildmat.2023.130991

Deng, C. J., Dang, F. N., Chen, X. Z., Miao, Z., & Chen, L. L. ,2020, Experimental Study on Grouting Effect and Mechanical Properties of the Rockfill Materials Grouted with SCM. *Advances in Civil Engineering*, *2020*. https://doi.org/10.1155/2020/8834686

Fan, G., Zhong, D., Yan, F., & Yue, P. ,2016, A hybrid fuzzy evaluation method for curtain grouting efficiency assessment based on an AHP method extended by D numbers. *Expert Systems with Applications*, *44*. https://doi.org/10.1016/j.eswa.2015.09.006

Fell, R., MacGregor, P., Stapledon, D., Bell, G., & Foster, M. ,2014, Geotechnical Engineering of Dams, 2nd Edition. In *Geotechnical Engineering of Dams, 2nd Edition*. https://doi.org/10.1201/b17800

Fu, Y., Wang, X., Zhang, S., & Yang, Y. ,2019, Modelling of Permeation Grouting considering Grout Self-Gravity Effect: Theoretical and Experimental Study. *Advances in Materials Science and Engineering*, *2019*. https://doi.org/10.1155/2019/7968240

Heidarzadeh, M., Mirghasemi, A. A., Eslamian, F., & Sadr-Lahijani, S. M. ,2013, Application of cement grouting for stabilization of coarse materials. *International Journal of Civil Engineering*, *11*(1 B), 71–77.

Jafarzadeh, F., & Garakani, A. A. ,2013, Foundation Treatment of Embankment Dams With Combination of Consolidation and Compaction Groutings. *International Conference of Case Histories in Geotechnical Engineering*.

Kalkani, E. (1991). Rock grouting and diaphragm wall construction Jaroslav Verfel. Elsevier, Amsterdam, the Netherlands, 1989, 532 pp, US$150, Dfl.285. *Engineering Geology*, *31*(3–4). https://doi.org/10.1016/0013-7952(91)90027-i

Kawasaki, M., Division, F. D., Yoshida, H., Division, F. D., & Yamaguchi, Y. (1998). *Grouting in consideration of predominant direction of joints in rock masses*. 410–415.

Kayabasi, A., & Gokceoglu, C. ,2019, An Assessment on permeability and grout take of limestone: A case study at Mut Dam, Karaman, Turkey. *Water (Switzerland)*, *11*(12). https://doi.org/10.3390/W11122649

Kazemian, S., & Huat, B. B. K. ,2009, Assessment and comparison of grouting and injection methods in geotechnical engineering. *European Journal of Scientific Research*, *27*(2), 234–247.

Kikuchi, K., Mimuro, T., & Mito, Y. ,1998, Geotechnical evaluation method of dam foundation for consolidation grouting. *ISRM International Symposium 1988*. https://doi.org/10.1016/0148-9062(90)90310-x

Kociánová, M., Černý, V., & Drochytka, R. ,2015, Development of grout for additional seal embankment dams. *Procedia Engineering*, *108*, 632–638. https://doi.org/10.1016/j.proeng.2015.06.191

Kociánová, M., & Drochytka, R. ,2016, *Technology of remediation of embankment dams by optimal grout*. *151*, 257–264. https://doi.org/10.1016/j.proeng.2016.07.370

Lagerlund, J. (2009). *Remedial Injection Grouting of Embankment Dams With Non-Hardening Grouts*.

Lees, D. ,2018, *The art of grouting and ground treatment*. *October*.

Mercedes, S. ,2023, *A comprehensive review of cementitious grouts : Composition , properties , requirements and advanced performance*. *375*(March), 0–2. https://doi.org/10.1016/j.conbuildmat.2023.130991

Meshkabadi, K., & Zandi, Y. ,2019, The effects of grout curtain parameters on uplift and piping phenomenon; case study: Sattarkhan Dam. *Hydrology*, *6*(3). https://doi.org/10.3390/hydrology6030071

Moos. (1984). Engineering and Design GROUTING TECHNOLOGY. *Ekp*, *13*(3), 576.

Nonveiller, E. (1989). *Grouting, theory and practice*. 250.

Obead, I. H., & Fattah, M. Y. ,2022, Mosul dam issues: analysis of the problem based on several studies. *IOP Conference Series: Earth and Environmental Science*, *1120*(1). https://doi.org/10.1088/1755-1315/1120/1/012027

Park, D. S., & Oh, J. ,2018, Permeation grouting for remediation of dam cores. *Engineering Geology*, *233*. https://doi.org/10.1016/j.enggeo.2017.12.011

Ricardo, J., Conde, M., & Silva, D. A. ,2019, *Use of cement based grouts in the rehabilitation of concrete dams : a review*. *November*, 1–8.

Shareef, A. H., Neami, M. A. A.-, & Rahil, F. H. ,2023, INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING Some of The Field and Laboratory Studies on Grouting Properties for Weak Soils : A Review. *International Journal of INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING*, *11*, 131–141.

Shinde, S., Naikwadi, S., Shevde, N., & Ansari, F. ,2008, Review on Utilization of Ceramic Waste in Grout. *International Research Journal of Engineering and Technology*, 1177. www.irjet.net

Sina Kazemain,2012, Review of soft soils stabilization by grouting and injection methods with different chemical binders. *Scientific Research and Essays*, *7*(24), 2104–2111. https://doi.org/10.5897/sre11.1186

Spross, J., Johansson, F., Uotinen, L. K. T., & Rafi, J. Y. ,2016, Using Observational Method to Manage Safety Aspects of Remedial Grouting of Concrete Dam Foundations. *Geotechnical and Geological Engineering*, *34*(5), 1613–1630. https://doi.org/10.1007/s10706-016-0069-8

Stare, D. P., Hockenberry, A. N., Dreese, T. L., Wilson, D. B., & Bruce, D. A. ,2012, *Protection of Embankments During Drilling and Grouting*. https://doi.org/10.1061/9780784412350.0107

Wang, C., Liu, Q., Guo, C., Xia, Y., Hao, Y., Shi, M., & Zhao, P,2020, An experimental study on the reinforcement of silt with permeable polyurethane by penetration grouting. *Advances in Civil Engineering*, *2020*, https://doi.org/10.1155/2020/8834331

Weaver, K. D. ,2003, *A Retrospective on the History of Dam Foundation Grouting in the U.S.*

https://doi.org/10.1061/40663(2003)20

Xu, Z., Miao, Y., Wu, H., Yuan, X., & Liu, C. ,2020, Estimation of viscosity and yield stress of cement grouts at true ground temperatures based on the flow spread test. *Materials*, *13*(13). https://doi.org/10.3390/ma13132939

Yu, J., Shen, Z., Xu, L., & He, C. ,2022, A Method for Determining Ultimate Grouting Pressure for Reinforcement of Masonry Arch Dam with Mortar Deterioration: A Case Study. *Materials*, *15*(10). https://doi.org/10.3390/ma15103520

Zhu, Y., Wang, X., Deng, S., Chen, W., Shi, Z., Xue, L., & Lv, M, 2019, Grouting process simulation based on 3D fracture network considering fluid-structure interaction. *Applied Sciences (Switzerland)*, *9*(4). https://doi.org/10.3390/app9040667