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Grouting Methods in Geotechnical Engineering: A Comprehensive Review and Outlook

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Abstract

The technique of rock and soil mass reinforcement has been widely used in engineering field and has solved many difficult problems in geotechnical engineering. As an important part of rock and soil consolidation technology, grouting method is also the most common foundation treatment method. Through pneumatic, hydraulic or electrochemical principles, some curable grout is injected into natural or artificial cracks or pores to improve various physical and mechanical parameters of the medium, so as to meet the needs of practical engineering. This paper reviews the development of grouting method, discusses the research status and technical characteristics of grouting method, and looks forward to the future development of grouting method from three aspects: grouting materials, admixtures and grouting technology.

Keywords

Grouting Method, Rock and Soil Reinforcement, Grouting Material.

1. Introduction

Grouting, as a time-honored technique for reinforcement and leak sealing, has evolved over more than 200 years. Its essence involves injecting certain curable grouts into natural or man-made cracks and voids using pneumatic, hydraulic, or electrochemical principles to enhance the physical and mechanical properties of various media. The objectives of grouting include preventing seepage, sealing leaks, reinforcing structures, and correcting building tilts. For seepage prevention, it primarily reduces pore pressure, decreases seepage flow, lowers permeability, and enhances impermeability. For leak sealing, it focuses on filling voids and intercepting water flow. For reinforcement, it improves the mechanical properties of rock and soil, restoring the integrity of concrete structures and masonry buildings. For correcting building tilts, it primarily employs the consolidation grouting method from grouting theory to cause localized uplift of strata, thereby eliminating or reducing uneven building settlement. Grouting applications include dam foundations, building foundations, roadbeds, underground structures, pre-fill aggregate grouting, post-tensioned anchor grouting, and post-grouting for cast-in-place piles. In recent years, it has seen widespread use in underground construction projects such as subways.

With continuous technological advancement, grouting methods have also evolved. He Shaohui et al. [1] conducted research on the reliability of jet control based on spoil soil improvement using the Lanzhou Metro as a case study. They determined the optimal concentration of bentonite slurry for grout-improved spoil soil and the optimal volume ratio for adding bentonite slurry, demonstrating that the improved spoil soil exhibits high jet control reliability due to its enhanced impermeability. Zhou Fei et al. [2] selected the splitting grouting reinforcement method for a specific underground civil defense project. They concluded that splitting grouting enables saturated weak soil layers to fracture under pressure within a short timeframe, allowing cement mortar to fill the fractures. This achieves consolidation and reinforcement, enhancing bearing capacity and modulus of deformation. Li Xunchang et al. [3] investigated the reinforcement mechanism and technical indicators of grouting for cavern treatment in highway subgrades within loess regions. Applying grouting to subgrade caverns, they proposed key design parameters for grouting reinforcement. Analysis of grouting treatment effects on loess caverns at construction sites demonstrated the method's excellent efficacy. Guo Jingzhuo et al. [4] conducted field tests on multi-row grouting, systematically investigating the variation and superposition patterns of horizontal soil displacement and pore pressure changes caused by single-row sequential grouting versus multi-row sequential grouting. They proposed an empirical formula for calculating pore pressure induced by grouting.Cheng Xuesong et al. [5] simulated grouting processes using strain methods based on field tests in Tianjin, concluding that horizontal soil displacement near injection points increases rapidly with grout volume while slowing at greater distances.

In summary, scholars have made considerable progress in grouting technology research. This advancement can be categorized into four key areas: First, the variety of grouting materials used has expanded significantly, with increasingly in-depth studies on material mix ratios, performance characteristics, and practical application issues. Second, significant progress has been made in fissure grouting technology, particularly in soft soil foundations where it is increasingly employed to enhance bearing capacity and mitigate building settlement. Third, computerized monitoring systems are now widely adopted in China and several developed nations during grouting operations to collect and process critical parameters such as injection pressure, grout consistency, and consumption rates, thereby improving work efficiency and technical proficiency. Fourth, the application scope continues to broaden [6-8]. Beyond dam foundation seepage control and reinforcement, grouting plays a crucial role in other civil engineering projects including roads, bridges, mines, cultural heritage sites, municipal works, subways, and underground power plants. With ongoing technological advancements, grouting methods undergo continuous innovation and iteration, expanding both their application range and technical sophistication. This paper explores the developmental trajectory and current status of grouting techniques while projecting future trends.

2. The Evolution of Grouting Materials

The development of grouting materials can be broadly categorized into four stages: the primitive clay slurry stage, the early cement slurry grouting stage, the intermediate chemical slurry grouting stage, and the modern grouting stage. The evolution through these stages not only reflects the gradual maturation of grouting technology but also demonstrates humanity's deepening understanding and application of materials science.

2.1. Primitive Clay Slurry Stage

In 1802, French civil engineer Charles Beringi successfully employed grouting technology to inject clay slurry into the ground, repairing and reinforcing the masonry walls of the port city of Dieppe. Using impact pumps to inject clay and lime slurry, this technique has now been in use for over two centuries [9]. Subsequently, this technology spread to Britain, Egypt, and other regions, marking the dawn of grouting technology.

2.2. Primary Cement Slurry Grouting Stage

In 1845, Watson of the United States first poured cement mortar beneath the foundation of a spillway chute. From 1856 to 1858, British engineer Kinipool successfully conducted cement grouting experiments. In 1864, Barlow employed cement slurry for backfilling grouting in tunnel lining walls, applying this technique to the London and Paris subways. Since then, cement slurry grouting technology has gained widespread global adoption.

2.3. Intermediate Chemical Grouting Stage

In 1920, Dutch mining engineer J.J.J. Jansen pioneered the use of a dual-liquid, dual-system secondary grouting method employing sodium silicate and calcium oxide. This technique remained widely employed until the 1940s. By 1969, the United States had developed over ten distinct chemical grouts, including acrylamide slurries. This phase introduced chemical materials such as sodium silicate and calcium oxide, significantly enhancing the effectiveness of grouting technology.

2.4. Modern Grouting Stage

The emergence of high-pressure jet grouting technology in the late 1960s marked a transition from loose to structured grouted rock masses. Grouting materials evolved toward ultra-fine cement, gradually replacing chemical grouts to reduce environmental pollution and lower project costs. Grouting technology is now widely applied in urban underground engineering, foundations, mining, road and bridge construction, tunnels, slope stabilization, and water conservancy projects.

3. Current Research Status of Grouting Methods

As a widely adopted reinforcement method in engineering, previous research on grouting techniques has primarily focused on two aspects: grouting materials and grouting mechanisms.

3.1. Grouting Material

The essence of geotechnical grouting involves injecting a curable grout mixture into the pores or fractures of rock and soil formations under pressure through drilled boreholes. This process enhances the physical and mechanical properties of the rock and soil mass. In other words, the injection and curing of the grout form the foundation for altering the mechanical properties of the reinforced rock and soil mass. Therefore, the type and characteristics of the grout material play a crucial role in the effectiveness of the reinforcement.

Grouting materials are composed of a primary agent (raw material), a solvent (water or other solvent), and admixtures. The term “grouting material” typically refers to the primary agent within the grout mixture. Grouting materials must be capable of solidification and are broadly categorized into inorganic and organic systems. Inorganic grouting materials include single-component cement-based, cement-water glass-based, and clay-based types. Organic grouting materials encompass acrylamide-based, lignin-based, urea-formaldehyde resin-based, polyurethane-based, polyvinyl alcohol-based, methyl methacrylate-based, and acrylic salt-based types. In everyday usage, grouts are typically categorized as particulate grouts, chemical grouts, and hybrid grouts. Particulate grouts primarily use cement as the main agent and are thus commonly referred to as cement-based grouts. Chemical grouts are formulated from two or more chemical materials. Their defining characteristic is that the grout forms a true solution (a relatively transparent solution) with low initial viscosity, enabling injection into fine cracks or pores. However, they are relatively expensive. Hybrid grouts are created by mixing particulate grouts with chemical grouts in varying proportions, such as cement-water glass grouts. They offer low cost and rapid setting properties, making them widely adopted.

3.1.1. Inorganic Grouting Materials

Inorganic grouting materials are primarily categorized into single-component cement-based slurries, cement-clay slurries, cement-water glass slurries, and water glass slurries.

Single-liquid cement grout refers to a mixture primarily composed of cement with added admixtures, prepared by mixing with water and injected as a single liquid. This type of grout is characterized by low cost, high hardened strength, and simple operation. Its disadvantages include poor pumpability and extended initial and final setting times, making precise control difficult.

Cement-clay slurries involve adding clay to cement slurry according to construction objectives and requirements. Sometimes clay content exceeds cement volume, resulting in cement-clay slurries. These offer excellent flowability and strong impermeability but exhibit lower strength compared to single-component cement slurries.

Cement-water glass grout refers to an injection material primarily composed of cement and water glass, injected in a dual-liquid system at specific ratios, with additives incorporated as needed. It offers excellent controllability, high stone formation rate, and superior stone strength.

Water glass grout uses water glass as the primary agent, combined with a setting agent to form a gel upon reaction. It can be used for single-liquid grouting or as a rapid-setting agent for cement grouting. When using water glass as the primary agent, different curing agents can be selected based on project requirements. Gelation time and performance can be determined through formulation testing. Due to its low cost and environmental friendliness, it is widely used in practical engineering. However, the following points require attention during application: First, after gelation, the slurry releases a certain amount of free sodium ions. While non-toxic, these ions can contaminate groundwater. Second, when acidic water glass slurry is used in soils with high moisture content, its pH value is susceptible to dilution by groundwater, making it difficult to accurately predict the gelation time. Third, due to the viscoelastic nature of silica gel, its strength may decrease when subjected to long-term loads after grouting. Therefore, when using water glass slurry to reinforce sandy soils, the creep characteristics of the reinforced material should be fully considered.

3.1.2. Organic Grouting Material

Organic grouting materials are primarily categorized into acrylamide-based slurries, lignin-based slurries, polyurethane-based slurries, and urea-formaldehyde resin-based slurries.

Acrylamide-based slurries are liquids formulated with the organic compound acrylamide as the primary agent, combined with other crosslinking agents, accelerators, and initiators. They exhibit excellent water resistance, good pumpability, and controllable gelation times. However, their drawbacks include poor durability, toxicity, and relatively high cost.

Lignin-based grouts are primarily composed of waste pulp liquor with added curing agents. They include chromolignin and sulfolignin grouts. Chromolignin grouts possess significant toxicity, limiting their large-scale application. Building upon this, sulfur lignin slurry using sodium persulfate as a curing agent has emerged, creating a non-toxic lignin slurry with significant development potential.

Polyurethane slurry is a grouting material with strong impermeability and high consolidation strength. It contains unreacted isocyanate groups that undergo a chemical reaction upon contact with water, cross-linking to form a water-insoluble polymer. It features simple operation and excellent impermeability.

Urea-formaldehyde resin is a polymer formed by the condensation of urea and formaldehyde. This material offers high strength and low cost. However, its strength varies significantly, quality is unstable, it cannot be stored long-term, and it must cure in an acidic medium. This causes corrosion to equipment and poses safety risks to humans. Consequently, its application scope is limited.

3.1.3. Other Modified Grouting Materials

Other modified grouting materials include ultrafine cement, non-toxic polyacrylate, modified epoxy resin, and others.

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3.2. Grouting Mechanism

In geotechnical reinforcement techniques, grouting mechanisms can be categorized into four types: permeation grouting, fracturing grouting, compaction grouting, and electrochemical injection.

Permeation grouting refers to the process where grout overcomes various resistances to infiltrate pores and fractures under grouting pressure. Higher pressure results in greater grout absorption and diffusion distance. This theory assumes the formation structure remains undisturbed and intact during grouting, employing relatively low grouting pressures. It is suitable for medium-sand and finer sandy soils, as well as fractured rock. It is further subdivided into the Spherical Diffusion Theory, Cylindrical Diffusion Theory, and Sleeve Method Theory.

The theory of fracturing grouting posits that under grouting pressure, the grout overcomes the initial stress and tensile strength of the formation, causing disruption and disturbance to the rock or soil structure. This leads to the expansion of existing pores or fractures within the formation, or the creation of new cracks or voids. Consequently, the groutability of low-permeability formations and the grout diffusion distance are enhanced, requiring relatively high grouting pressure.

Compaction grouting is categorized into in-situ compaction and surface compaction. Surface compaction involves injecting grout onto the soil surface beneath a building's foundation slab, inducing consolidation and settlement of the soil from top to bottom. In-situ compaction involves injecting thick grout into the soil through boreholes. As the soil compacts and grout is forced in, bulbous voids form around the injection points. The grout's pressure generates radial uplift forces, causing localized ground heaving. This principle has been applied in numerous projects to correct uneven settlement of above-ground structures, hence the term “in-situ compaction.” Simply put, compaction grouting is the process of displacing and compacting soil using dense grout.

Finally, the electrochemistry grouting theory operates on the principle that when metal electrodes are inserted into clay and a direct current is applied, electroosmosis and ion exchange occur within the soil. electrophoresis, and ion exchange within the clay. This reduces moisture content in the electrified zone, forming grouting channels within the soil. When silicate grout is injected into the soil during electrification, silica gel forms along these channels. This gel bonds with soil particles, creating a reinforced mass with significant mechanical strength.

4. Prospects for Grouting Methods

Grouting, as a time-honored geotechnical reinforcement technique, is poised to expand its development prospects and application scope with ongoing technological advancements. Future development will primarily focus on three key areas: grouting materials, admixtures, and grouting techniques.

4.1. New Developments in Grouting Materials

4.1.1. Technological Innovation Drives Market Development.

(1) Eco-friendly Formulations: With heightened environmental awareness, the grouting materials industry has prioritized developing environmentally conscious products. By adopting low-VOC and solvent-free formulations, environmental impact is minimized while ensuring worker health.

(2) Rapid Curing Technology: To enhance construction efficiency, some companies have developed fast-curing grouts that significantly reduce curing time and boost work productivity.

(3) High-Performance Materials: Leveraging nanotechnology and high-performance fibers, grouting materials with enhanced strength and durability have been developed for use in more demanding engineering conditions.

(4) Intelligent Grouting Systems: Integrating modern electronic technology, smart grouting monitoring systems have been developed to provide real-time oversight of the grouting process, ensuring construction quality.

4.1.2. Market Demand Drives Product Upgrades

(1) Growing Demand for Infrastructure Construction: As infrastructure development intensifies globally, grouting materials-a vital engineering material-will see sustained demand growth. Particularly in transportation, water conservancy, and real estate sectors, the grouting materials market is poised for significant expansion opportunities.

(2) Development in Marine Engineering: With the expansion of marine resource development and marine engineering projects, grouting materials resistant to seawater corrosion will enjoy broad market prospects.

(3) Applications in New Energy Sectors: Advancements in new energy fields will drive demand for grouting materials in wind power generation, solar power generation, and related sectors.

4.1.3. Development Trends

New grouting materials continue to emerge, with environmental sustainability, multifunctionality, high strength, and intelligent properties representing the four key directions for future development.

(1) Environmental Sustainability: Future grouting materials will increasingly prioritize eco-friendliness, utilizing renewable, biodegradable, low-energy, and low-pollution materials to reduce environmental impact and conserve resources.

(2) Multifunctionality: Future grouting materials will increasingly integrate multiple functions-such as waterproofing, thermal insulation, soundproofing, and crack resistance-into a single solution. This approach reduces building maintenance and repair costs while enhancing structural longevity and occupant comfort.

(3) High Strength: As construction projects demand increasingly higher structural strength and durability, developing high-strength grouting materials will become a primary future trend.

(4) Smart Capabilities: With the continuous advancement of IoT and sensor technologies, future grouting materials will gradually incorporate smart functionalities.

4.2. New Developments in Admixtures

The development direction of admixtures is largely similar to that of grouting materials, with key focuses on environmental friendliness, multifunctionality, high strength, and intelligent properties. For instance, ultrafine cement-developed to address the issue of ordinary cement particles being too large to penetrate microcracks-first appeared in Japan during the mid-to-late 20th century. Through subsequent research, adding new admixtures to ultrafine cement can enhance its strength or flowability. Research by Zhang Yingwei et al. [10] indicates that incorporating approximately 0.5% high-efficiency water-reducing agent into ultrafine cement effectively reduces slurry viscosity and enhances flowability. Incorporating 0.5%–2.5% setting regulators during the preparation of ultrafine cement grouting materials ensures appropriate setting times; Adding active admixtures such as fly ash and silica fume to ultrafine cement reduces hydration heat.

4.3. New Developments in Grouting Technology

4.3.1. High-Pressure Spray Drilling

Vibratory Drilling High-Pressure Jet Grouting Technology is an innovative foundation treatment method. Primarily based on conventional high-pressure jet grouting technology, it enhances the combined effectiveness of drilling and high-pressure jet grouting by integrating high-pressure jet grouting, high-power high-frequency vibratory drilling, and specialized equipment. This approach offers advantages such as rapid hole formation and high hammering vibration force. In geotechnical engineering, the three-pipe high-pressure jet grouting process is commonly employed, simultaneously completing both vibratory drilling and jet grouting. This technique is primarily suitable for cohesive soils, silty soils, sandy soils, silty sands, and formations with high gravel content. During construction, ordinary Portland cement is commonly selected as the grouting material, with water pressure controlled between 25 and 40 MPa. This method has been widely applied in hydraulic engineering projects.

4.3.2. Dual-High-Pressure High-Spray Grouting RJP Technology

High-pressure rotary jet grouting technology is widely applied in geotechnical engineering construction in China. However, from the perspective of soft foundation reinforcement requirements, it still has certain limitations and cannot fully meet the engineering demands for pile diameters exceeding 1.8 meters. Additionally, its application faces construction challenges such as high cement consumption, uneven mixing, and cement slurry being carried out. The introduction of RJP technology addresses these shortcomings by simultaneously injecting high-pressure water and high-pressure cement slurry. This innovation extends the applicable pile diameter range to 2–3 meters and has been formally adopted in engineering projects. It significantly broadens the application scope of high-pressure jet grouting, reduces construction costs, and enhances project efficiency [11].

4.3.3. Coal Seam Fire Extinguishing Grouting

To prevent spontaneous combustion of coal mine materials and isolate the ore body from air, coal seam fire extinguishing grouting technology is widely adopted both domestically and internationally. This technology primarily involves spraying several types of grout to cover coal mine fissures, thereby cutting off contact with air to achieve fire suppression. The grouting materials used for coal seam fire extinguishing exhibit strong water absorption, are non-combustible themselves, and are cost-effective, making them widely applicable in coal mining engineering. The introduction of the coal seam fire extinguishing grouting concept and its technological application hold significant importance for the Western Development Strategy. Beyond this grouting technique, chemical materials may also be employed for fire suppression.

4.3.4. Pile Foundation Enlarged-Base Grouting

The purpose of pile base enlargement grouting is to enhance the stability and bearing capacity of the foundation beneath the pile base, while also improving the pile's seismic resistance. Compared to conventional pile-bottom techniques, enlarged-base grouting achieves consolidation with the surrounding soil and rock. This method not only improves foundation stability but also reduces concrete consumption, yielding significant cost savings. Coupled with its excellent stabilization effects, it has been widely adopted in pile foundation construction for high-rise buildings.

4.3.5. Tree Root Pile Reinforcement Technology

Tree root pile reinforcement technology employs a rotary method to embed steel bars into the foundation, thereby achieving foundation reinforcement and correcting skew. Since the angle of tree root piles can be freely inclined, this technology maximizes the maintenance of structural and foundation equilibrium during construction. Furthermore, the three-dimensional structure utilized in tree root pile reinforcement effectively enhances foundation stability. The construction process of root pile reinforcement technology is relatively straightforward, requiring no large-scale machinery. Given its operational convenience, superior reinforcement capabilities, strong balancing properties, and cost-effectiveness, this technology undoubtedly holds broad prospects for future development.

4.3.6. High-Pressure Grouting Pile Sealing and Water Blocking Technology

China possesses an extensive coastline, making the reinforcement of coral reef foundations a critical topic in geotechnical engineering. Groundwater beneath coral reef foundations is predominantly alkaline, necessitating the introduction of freshwater and the sealing of alkaline water seepage through high-pressure grouting and pile sealing techniques. Coral reef strata primarily consist of fine sand, medium-coarse sand, and coral debris, demanding high standards for waterproofing and seepage prevention. Therefore, in the construction of coral reef foundations on islands such as the Xisha Islands, the high-pressure grouting pile sealing technology has been adopted. This technology has garnered significant acclaim since its initial application in China and holds promise for widespread future adoption in engineering projects involving coral reef strata. It also offers the advantage of reducing concrete consumption.

4.3.7. Static Pressure Grouting

The foundation of static pressure grouting technology lies in high-pressure jet excavation. This technique effectively corrects issues such as foundation soil layer deformation caused by time-related changes, completely resolves foundation settlement problems in engineering projects, and offers excellent stability, making it a crucial method for reinforcing foundations. The control of the tilt at the Leaning Tower of Pisa was achieved using high-pressure jet grouting technology, which will play a crucial role in the construction of future conceptual skyscrapers.

4.3.8. Powder Blasting Reinforcement Technology

Powder injection reinforcement technology generates stable hydration products through chemical reactions. These hydration products possess high strength and greater capacity to absorb moisture surrounding the material, making the technique widely applied in various soft soil foundation geotechnical engineering projects. The powder mixture primarily consists of cement, quicklime, and fly ash.

5. Conclusion

In summary, grouting has achieved significant development as an effective geotechnical reinforcement technique for strengthening and sealing leaks. With an increasing number of geotechnical reinforcement challenges emerging, China has taken a leading position globally in geotechnical reinforcement and foundation treatment. Current reinforcement technologies generally meet the requirements of construction projects. However, further research is needed to develop more advanced reinforcement techniques tailored to diverse geological conditions and complex structures. Therefore, relevant technical personnel should deepen their understanding of the significance of geotechnical reinforcement technologies. Building upon existing foundations, they should pioneer the development of grouting materials and admixtures that are more suitable for engineering applications, more cost-effective, and more environmentally friendly. Innovating novel grouting techniques tailored to specific projects will enable stronger capabilities to undertake geotechnical reinforcement projects both domestically and internationally, continuously driving new advancements in geotechnical reinforcement technology.

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