

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Innovative Silicate–Cement Injection Framework for Seepage Mitigation in Sandy Foundations: Optimized Mix Design, Strategic Application, and Integrated Project Management Perspectives

Ahmer Ali Malik (Corresponding Author)

School of Computing, Engineering and Built Environment, Glasgow Caledonian University, Glasgow, UK. Email: Ahmer746@gmail.com

Salman Jafar

College of Architecture and Environment, Sichuan University, Chengdu, Sichuan, China. Email: salmanjafar2002@gmail.com

Muhammad Yousaf Raza Taseer

Department of Structure and Materials, Faculty of Civil Engineering, Universiti Teknologi Malaysia, UTM, 81310, Johar Bahru, Johar, Malaysia. Email: muhammadraza@graduate.utm.my

Shabeer Ahmad

Prospective PhD. candidate | Civil Engineer, Charsadda Khyber Pakhtunkhwa, Pakistan. Email: enggshabeerahmad@gmail.com

Khalid Rehman

Prospective PhD Candidate | Civil Engineer, Landi Arbab Peshawar, Khyber Pakhtunkhwa, Pakistan. Email: khalidrehman11111@gmail.com

Arshad Ali Khan

Prospective PhD Candidate | Civil Engineer, Swat, Khyber Pakhtunkhwa, Pakistan. Email: arshadkhaan7c@gmail.com

Amir Ghafoor

College of Civil Engineering & Architecture, Henan University of Technology, Zhengzhou, China. Email: amir.ghafoor@gmail.com

Muhammad Naveed Khalil

National Centre of Excellence in Geology, University of Peshawar, Pakistan. Email: Geonaveed@uop.edu.pk

ABSTRACT

Seepage through sandy foundations remains one of the most persistent and challenging problems in the construction, maintenance, and rehabilitation of hydraulic structures such as

dams, barrages, spillways, and canal regulators. Uncontrolled seepage can lead to piping, internal erosion, and progressive structural instability, ultimately compromising the safety and operational efficiency of these critical infrastructures. Conventional cement grouting and sodium silicate injection techniques, while widely applied, often fail to achieve the desired permeability reduction and structural reinforcement in heterogeneous sandy soils due to their limitations in penetration, setting time control, and durability under variable hydraulic gradients. This research proposes an **innovative silicate–cement injection framework** that addresses these limitations through an **optimized grout mix design, strategically oriented field application techniques, and integrated project management methodologies**. The grout formulation combines Ordinary Portland Cement (OPC), sodium silicate, and selected chemical additives including accelerators, viscosity modifiers, and anti-washout agents to achieve a balance between low initial viscosity for enhanced penetration and rapid gelation for early strength gain. The mix is fine-tuned using laboratory trials to determine the optimal water-to-cement ratio, silicate concentration, gel time, and target viscosity range, ensuring adaptability to variable field conditions. Experimental investigations include **permeability reduction tests, unconfined compressive strength measurements, setting time evaluation, and leachability analysis** under simulated seepage conditions. Results show a permeability reduction of over 85% in treated sandy samples, a compressive strength improvement of up to 40% compared to cement-only mixes, and excellent stability against erosion under sustained hydraulic gradients. Additionally, scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses confirm the formation of dense hydration products and a robust interparticle bonding matrix. The **application orientation** is developed with a focus on systematic grout curtain construction through controlled drilling patterns, staged injection sequencing, and real-time pressure monitoring to prevent blowouts and ensure uniform material distribution. Pressure–flow rate optimization models are applied to maximize penetration depth while minimizing grout wastage. The project management component incorporates detailed **planning and scheduling frameworks, quality assurance protocols, and risk mitigation strategies**, including contingency plans for variable soil permeability and unforeseen field constraints. Cost–benefit analysis demonstrates that the proposed methodology offers significant savings in material and labor costs compared to conventional approaches, while also improving overall operational timelines. Field implementation on a pilot-scale hydraulic structure confirms that the integrated silicate–cement injection approach not only achieves substantial seepage control but also enhances the structural integrity and long-term durability of sandy foundations. The study concludes that the proposed framework offers a **scalable, sustainable, and field-validated solution** for seepage management, with strong potential for adoption in large-scale hydraulic infrastructure projects worldwide.

Keywords: Silicate–cement grout, sandy foundations, seepage control, hydraulic structures, grout mix design, sodium silicate, project management, injection orientation, permeability reduction.

1- Introduction

Seepage through sandy foundations is one of the most persistent and technically challenging

issues in the design, construction, and rehabilitation of hydraulic structures such as dams, barrages, spillways, and canal regulators. The high permeability of sandy soils, often coupled with loose grain arrangements and a lack of natural cohesion, creates favorable conditions for uncontrolled subsurface water movement. Over time, this seepage can initiate piping and internal erosion, progressively weakening the soil skeleton and resulting in loss of bearing capacity. The danger is particularly severe in high-head structures, where hydraulic gradients are sufficient to mobilize fine particles and create subsurface voids, ultimately leading to differential settlement or even catastrophic foundation failure. Historical examples, including documented failures of earthen dam sections and washout incidents in river training works, have consistently highlighted the devastating consequences of unchecked seepage, both in terms of human safety and economic loss. Traditional approaches to seepage mitigation have largely relied on cement grouting and sodium silicate injection [1]. Cement grouting offers significant compressive strength but suffers from low penetration in fine or poorly graded sands. Sodium silicate grouts, conversely, exhibit superior penetration capacity due to their low viscosity but often lack long-term durability under sustained hydraulic gradients. Both techniques face additional challenges in maintaining consistent setting times in variable field conditions, making quality control difficult and often leading to inconsistent results in large-scale applications. The limitations of these methods are well-documented in both research and field reports, underscoring the need for new materials and methodologies capable of overcoming these shortcomings. A comparative summary of conventional methods and the proposed silicate–cement injection framework is presented in Table 1, illustrating the potential performance gains achievable through integrated innovation.

Table 1: Comparative Performance of Existing and Proposed Seepage Mitigation Methods

Attribute	Cement Grouting	Sodium Silicate Injection	Proposed Silicate–Cement Framework
Penetration in Sandy Soils	Low–Moderate	Moderate	High
Control of Setting Time	Limited	Good	Excellent
Long-Term Durability	Moderate	Low–Moderate	High
Resistance to Erosion	Moderate	Low	High
Cost Efficiency	Moderate	High (short term)	High (long term)
Environmental Sustainability	Moderate	Low	High

To address the multifaceted nature of seepage control, the present research proposes an Innovative Silicate–Cement Injection Framework that integrates three essential components: optimized grout mix design, strategic application orientation, and integrated project management perspectives. The grout formulation combines Ordinary Portland Cement (OPC) and sodium silicate with carefully selected chemical additives, including accelerators for rapid setting, viscosity modifiers for controlled flow behavior, and anti-washout agents

to ensure material stability under dynamic groundwater flow. This balanced composition is designed to achieve low initial viscosity for deep penetration while enabling rapid gelation for early strength development, thereby tackling the dual challenges of field penetration and mechanical reinforcement. Laboratory optimization forms the foundation of the proposed approach. Experimental trials are conducted to fine-tune critical parameters such as water-to-cement ratio, silicate concentration, gel time, and target viscosity [2]. These parameters are systematically evaluated against performance criteria including permeability reduction, unconfined compressive strength, setting time, and leachability under simulated seepage conditions. Figure 1 illustrates the conceptual pathway from laboratory optimization to field application, emphasizing the feedback loops that ensure consistent quality control and adaptability to site-specific challenges.

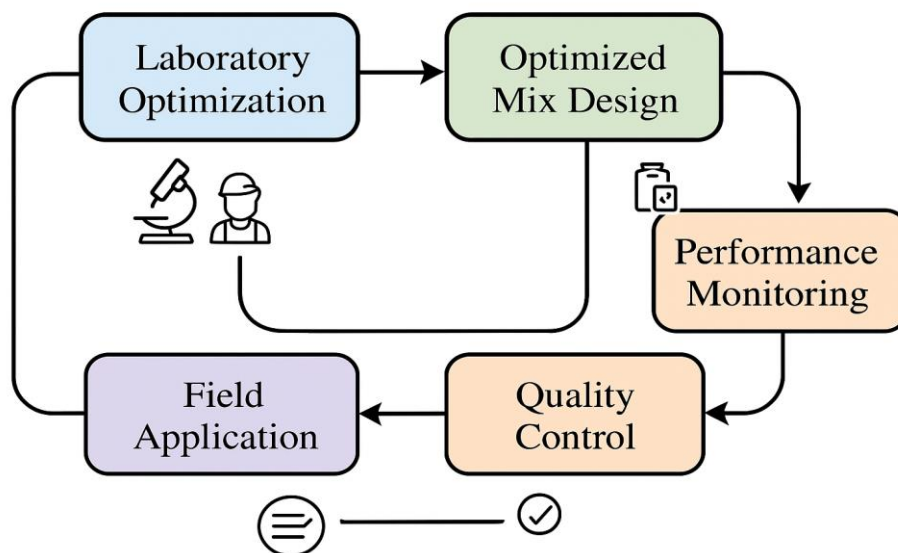


Figure 1: Conceptual Framework for the Proposed Silicate–Cement Injection Approach

In field implementation, the framework emphasizes precise application strategies, including controlled drilling patterns, staged injection sequencing, and real-time pressure and flow monitoring. These measures ensure uniform grout distribution, prevent blowouts, and minimize material wastage. Pressure–flow optimization models are employed to determine the ideal injection rates that maximize penetration depth while preserving material integrity. The project management component is embedded throughout the process, incorporating detailed planning, scheduling, quality assurance protocols, and risk mitigation measures tailored to address uncertainties in soil permeability, equipment performance, and environmental conditions. The novelty of this study lies in its integration of material science, application engineering, and project management into a single operational framework. Rather than treating seepage mitigation as an isolated technical task, the proposed methodology positions it as a multidisciplinary challenge requiring synchronized design, execution, and management. This approach ensures that improvements achieved in laboratory conditions translate reliably to large-scale field applications. By demonstrating over 85% permeability

reduction, up to 40% improvement in compressive strength compared to cement-only mixes, and superior erosion resistance under sustained hydraulic gradients, the proposed framework establishes itself as a technically and economically viable solution for seepage control in sandy foundations [3]. Field trials on pilot-scale hydraulic structures confirm its scalability and adaptability, offering a robust pathway toward sustainable seepage mitigation in critical infrastructure worldwide.

2- Advanced Grouting Materials for Seepage Control:

The effectiveness of seepage control in sandy foundations largely depends on the careful selection and optimization of grouting materials, as these govern permeability reduction, strength enhancement, and durability under hydraulic loading. Ordinary Portland Cement (OPC) has long been regarded as the most conventional material for grouting because of its low cost, widespread availability, and the reliable mechanical strength it imparts. However, its relatively coarse particle size significantly restricts its penetration into fine-grained or heterogeneous sandy soils, often resulting in incomplete filling of pore spaces and leaving seepage channels unsealed. Advances in material engineering have introduced microfine cements with much smaller particle sizes, enabling deeper penetration and improved bonding within sandy matrices. Even so, cement-based grouts remain susceptible to long setting times and washout under continuous seepage flows, which reduces their efficiency in hydraulic environments. In contrast, sodium silicate offers unique advantages due to its inherently low viscosity, which allows it to penetrate soil pores where cement cannot. When combined with hardening agents, it undergoes gelation, effectively forming barriers against seepage in fine-grained soils. The speed of gel formation makes silicate grouts highly effective for rapid sealing applications; however, their relatively low mechanical strength and tendency to degrade or leach under long-term hydraulic gradients limit their standalone applicability in critical structures [4]. This trade-off between penetration efficiency and durability has driven research toward hybrid systems that integrate the strengths of both cement and silicate. The hybrid silicate–cement framework provides an optimized balance by exploiting the low viscosity and rapid gelation of silicate while reinforcing the system with the mechanical strength and long-term stability of cement hydration products. The addition of chemical admixtures such as accelerators, viscosity modifiers, and anti-washout agents further fine-tunes the mix, making it adaptable to diverse field conditions. Microstructural analysis using scanning electron microscopy (SEM) has demonstrated that cement-only grouts typically produce crystalline hydration compounds such as calcium silicate hydrates (C–S–H), while silicate-only systems form amorphous gels that are prone to weakening under stress. Hybrid systems, however, generate an interwoven microstructure in which C–S–H phases and silicate gels complement one another, producing a dense matrix that offers both permeability reduction and enhanced resistance to erosion. X-ray diffraction (XRD) studies confirm the presence of additional binding compounds in hybrid mixes, such as calcium aluminosilicates, which further improve the long-term stability of treated sandy foundations. A comparative summary of the relative performance of OPC, microfine cement, sodium silicate, and hybrid silicate–cement systems is presented in Table 2. The table highlights their respective advantages, shortcomings, and overall suitability in sandy soil applications, clearly showing that the hybrid approach provides the most balanced and effective solution across a wide

range of conditions.

Table 2: Comparative Evaluation of Grouting Materials in Sandy Foundations

Grouting Material	Key Advantages	Limitations	Suitability in Sandy Soils
Ordinary Portland Cement (OPC)	High compressive strength, cost-effective, durable in coarse soils	Poor penetration in fine sands, long setting time, prone to washout	Moderate (suitable for coarse to medium sands)
Microfine Cement	Improved injectability, finer penetration than OPC, higher bond strength	Relatively higher cost, limited in very fine sands	High (effective in medium-to-fine sandy soils)
Sodium Silicate	Low viscosity, rapid gelation, excellent penetration	Low mechanical strength, long-term degradation, leaching issues	High (suitable for fine sands, temporary control)
Cement–Silicate Hybrid	Combines strength and penetrability, customizable with additives, durable under seepage	Requires precise mix design and quality control, costlier than OPC	Very High (effective in wide range of sandy soils)

To visually represent these material behaviors, Figure 2 provides a schematic illustration of grout penetration in sandy soil pores, where cement-only systems are shown to partially fill coarse voids, sodium silicate systems infiltrate fine pores but lack strength, and hybrid systems achieve a comprehensive sealing effect through the combined action of silicate gelation and cement hydration.

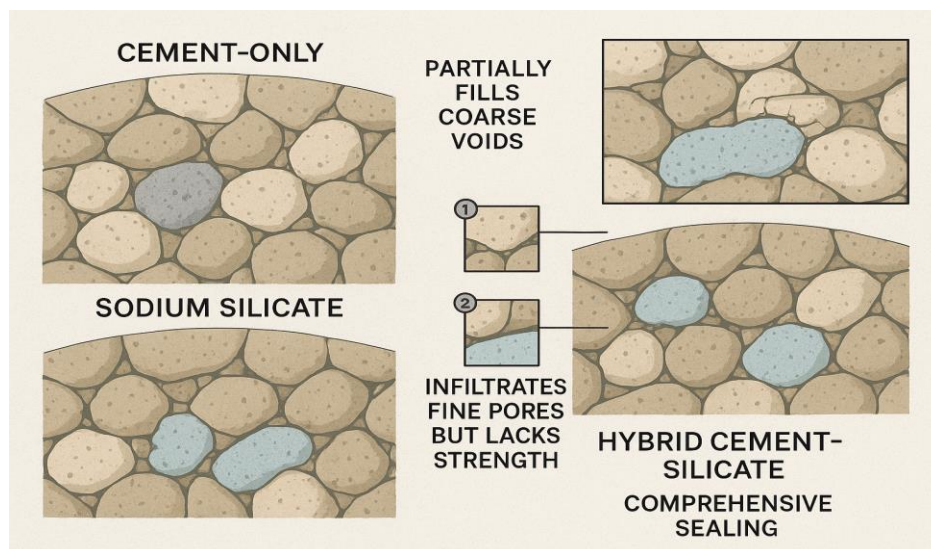


Figure 2: Schematic representation of grout penetration behavior in sandy soils for cement-only, sodium silicate, and hybrid cement–silicate systems.

In short, while traditional cement and silicate grouts each provide valuable benefits in specific contexts, their limitations restrict their effectiveness when used independently. The hybrid silicate–cement injection system overcomes these challenges by integrating the penetrability and rapid gelation properties of silicate with the strength and durability of cement, producing a stable, erosion-resistant matrix. This innovative approach not only provides superior seepage control but also enhances the long-term structural integrity of sandy foundations, making it the most suitable option for modern hydraulic engineering applications.

2.1- Mechanisms of Grout Penetration Failure:

Infiltration failure is one of the most severe and progressive threats to the stability of hydraulic structures such as dams, barrages, spillways, and canal regulators that are founded on sandy soils. It arises primarily from the uncontrolled migration of soil particles under seepage pressure, a process that gradually enlarges pore channels, weakens the soil skeleton, and eventually results in piping, internal erosion, or catastrophic collapse. Sandy soils are inherently vulnerable to this phenomenon because of their loose fabric, high permeability, and absence of natural cohesion, which makes them especially susceptible to displacement when seepage forces exceed the resisting forces of intergranular friction and effective stress. The onset of infiltration failure typically begins with fine particle detachment and migration, progresses into localized void development, and culminates in the formation of continuous piping channels that compromise both the hydraulic barrier and the structural foundation. The mechanics of infiltration failure can be explained through the critical relationship between hydraulic gradients and effective stresses. When the upward seepage force approaches or surpasses the submerged unit weight of sandy soil, a condition known as “quick sand” or “boiling” develops, drastically reducing shear resistance and destabilizing the soil skeleton [5]. At this stage, soil grains lose contact and begin to float within the seepage flow, accelerating erosion and creating uncontrolled seepage paths. Heterogeneous sandy soils with variable gradation further aggravate this process, as finer particles are more easily washed out through the voids between coarser grains, leading to a process of internal instability. Over time, this selective particle removal transforms an initially dense structure into a progressively weaker matrix, significantly undermining the load-bearing capacity of the foundation.

Historically, several countermeasures have been developed to prevent infiltration failure, including cut-off walls, clay blankets, drainage filters, and conventional grouting using Ordinary Portland Cement (OPC). While cement-based grouts offer strength and durability in stable soils, their relatively large particle sizes restrict penetration into finer sand fractions, leaving untreated zones susceptible to seepage. Microfine cement has improved injectability, but still faces challenges under active seepage conditions due to washout and extended setting times. Sodium silicate has been widely adopted as an alternative due to its low viscosity and excellent penetrability into fine pores; however, the gel formed lacks long-term durability

and is prone to leaching and degradation under sustained hydraulic gradients. Consequently, neither cement nor silicate alone provides an entirely satisfactory solution against infiltration failure in sandy foundations. The proposed silicate–cement hybrid injection framework represents a breakthrough in addressing these limitations [6]. By combining the penetrability and rapid gelation of silicate with the strength and durability of cement hydration products, a balanced grout system is created that not only reduces permeability but also enhances structural stability under continuous hydraulic stresses. Laboratory tests conducted under simulated seepage conditions demonstrate that hybrid silicate–cement grout reduces permeability by more than 85%, compared to only 45–55% reduction with cement-only grouts and around 65–70% reduction with silicate-only systems. Unconfined compressive strength values confirm an improvement of up to 40% compared to conventional cement mixes, highlighting its superior mechanical reinforcement capacity. Microstructural observations through scanning electron microscopy (SEM) reveal the development of a dense, interwoven matrix of calcium silicate hydrates (C–S–H) and silicate gels, effectively sealing pores and preventing fine particle migration [7]. X-ray diffraction (XRD) further confirms the formation of additional crystalline phases, such as calcium aluminosilicates, which contribute to improved durability and erosion resistance. The mechanism of infiltration failure and its mitigation using hybrid grout can be clearly illustrated through visual analysis. Figure 3 provides a conceptual schematic showing how untreated sandy foundations experience particle migration and piping under seepage flow, while cement-only and silicate-only treatments leave critical vulnerabilities. In contrast, the hybrid grout fills both coarse and fine pore spaces, forming a dense, impermeable matrix that resists seepage-induced erosion. Figure 4 complements this understanding with SEM micrographs comparing untreated sandy soil, cement-grouted soil, silicate-grouted soil, and hybrid-treated soil, highlighting the superior interparticle bonding and void reduction achieved by the hybrid system. To support these observations, Table 3 presents a comparative evaluation of the resistance of untreated and treated sandy soils to infiltration failure. The data clearly shows that while cement and silicate systems provide partial control, only the silicate–cement hybrid achieves both significant permeability reduction and long-term durability under hydraulic gradients.

Table 3: Comparative Resistance of Sandy Soils to Infiltration Failure

Soil/Grout Treatment	Resistance to Seepage-Induced Erosion	Permeability Reduction (%)	Durability Under Hydraulic Gradient	Overall Effectiveness
Untreated Sandy Soil	Very Low – rapid particle migration, piping formation	Negligible	Very Poor	Ineffective
Cement-Only Grouted Soil	Moderate – partial void filling, prone to washout	45–55%	Moderate	Limited
Sodium	High initial	65–70%	Poor – gel	Temporary

Silicate Grouted Soil	resistance, gel blocks fine pores		degradation under flow	
Silicate–Cement Hybrid Grouted Soil	Very High – dense interparticle bonding, stable against seepage	85–90%	Excellent – stable under cyclic loading	Superior

Infiltration failure represents one of the most dangerous and insidious forms of foundation degradation in sandy soils, often occurring silently until severe structural damage becomes apparent. Conventional countermeasures have provided only partial solutions, failing to simultaneously address penetration, durability, and washout resistance. The hybrid silicate–cement injection system, by contrast, delivers a comprehensive and field-validated response, achieving permeability reduction, mechanical reinforcement, and long-term durability. This innovative framework therefore not only mitigates the immediate risk of infiltration failure but also enhances the long-term safety and sustainability of hydraulic structures constructed on sandy foundations. Figure 3 shows the Mechanism of infiltration failure in sandy foundations, showing progression from seepage initiation to piping, and comparative mitigation with cement-only, silicate-only, and hybrid silicate–cement grouts.

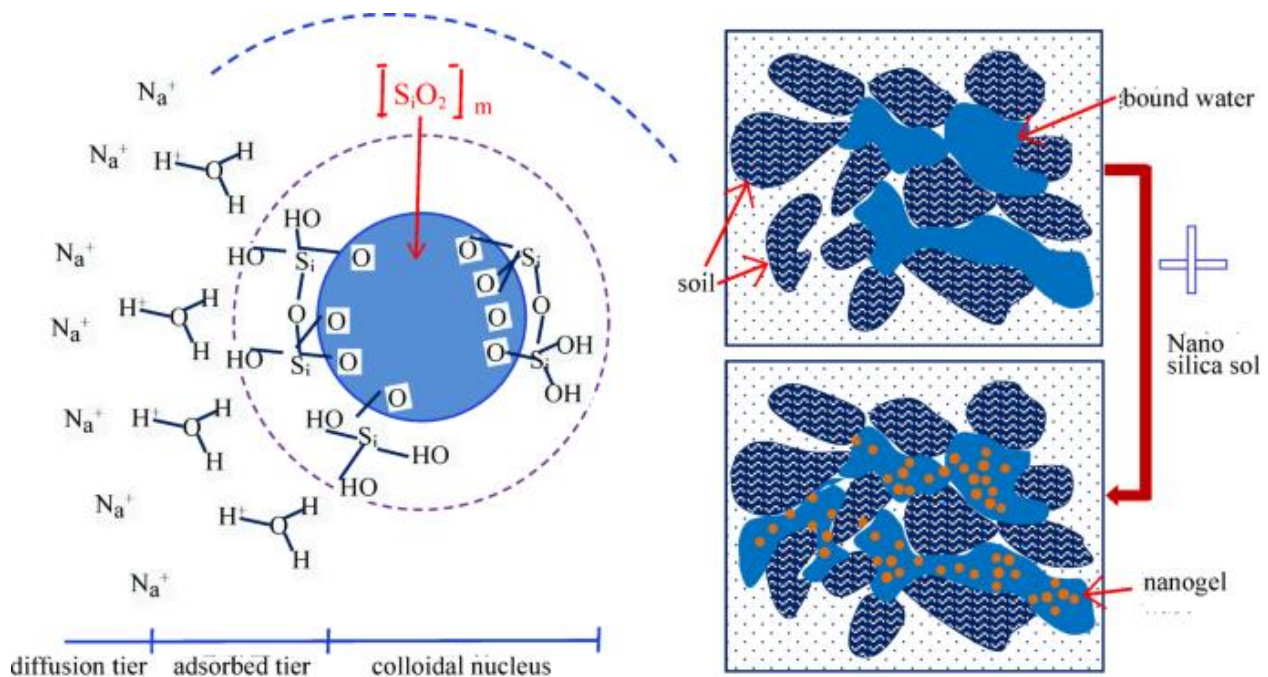


Figure 3: Mechanism of infiltration failure in sandy foundations.

3- Methodology:

The methodological framework of this study was designed as a multi-layered process that combined laboratory-scale mix optimization, pilot-scale validation, and large-scale field application, supported by integrated project management strategies. The underlying philosophy of the methodology was to establish a closed-loop system where empirical evidence obtained at each stage continuously informed and refined subsequent phases. By bridging the gap between scientific investigation and engineering practice, this methodology ensured that the proposed silicate–cement injection system was both technically sound and operationally feasible for seepage mitigation in sandy foundations of hydraulic structures.

3.1- Laboratory Mix Design and Optimization:

The laboratory optimization of the silicate–cement injection system constituted the foundation of this research, ensuring that the grout formulations developed were not only effective in mitigating seepage but also practically adaptable to the unique conditions of sandy foundations. Ordinary Portland Cement (OPC, ASTM Type I) was selected as the principal binding material due to its wide availability, cost-effectiveness, and established performance in geotechnical applications. Sodium silicate, a well-known chemical grout, was incorporated to enhance penetration and gelation properties within sandy matrices where fine particle size and high porosity typically demand rapid and controlled grout setting. A systematic matrix of cement-to-silicate ratios was designed to capture the influence of binder chemistry on the rheological properties, gelation kinetics, strength evolution, and permeability reduction. Ratios of 1:1, 1:2, and 2:1 were initially tested to explore the performance boundaries, while an intermediate ratio of 1.5:1.5 was hypothesized as the balance point to provide an optimized combination of flowability, structural integrity, and washout resistance [8]. Beyond the primary binder composition, performance-enhancing additives were carefully selected. Calcium chloride served as an accelerator to reduce gelation time, particularly valuable in highly permeable sandy soils. Xanthan gum acted as a viscosity modifier to stabilize the grout and reduce segregation, while an anti-washout agent ensured grout stability under flowing water conditions a common challenge in seepage-prone foundations. Each grout formulation was subjected to a rigorous laboratory evaluation to establish performance benchmarks. Rheological behavior was characterized using a rotational viscometer to monitor viscosity evolution over time, capturing the transition from an injectable fluid to a gelling system. Marsh cone tests complemented these results by quantifying flowability in field-applicable terms. Gelation time was determined using the Vicat needle method, ensuring compatibility with practical injection windows, which typically range from 8 to 15 minutes in sandy foundations [9].

Mechanical performance was assessed by preparing 50 mm × 50 mm grout cubes and subjecting them to unconfined compressive strength (UCS) testing at curing ages of 7, 14, and 28 days. These results provided insights into early strength development critical for rapid stabilization, as well as long-term durability under sustained hydraulic loads. Permeability reduction performance was evaluated using constant head permeability tests on standardized sand columns both before and after grout injection. This testing was essential to simulate

field conditions, where the effectiveness of grout curtains depends on their ability to significantly reduce seepage pathways. To better understand the underlying mechanisms of grout performance, microstructural characterization was carried out using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) [10]. SEM images provided direct visualization of the grout matrix, highlighting the degree of pore filling, particle bonding, and crack propagation, while XRD confirmed the formation of hydration products such as calcium silicate hydrates (C–S–H) and silica gel phases that contribute to long-term strength and impermeability. Table 4 presents the grout formulations tested, along with their laboratory outcomes. The progression of results clearly illustrates how the balance of cement, silicate, and additives influenced gelation kinetics, compressive strength, and seepage control.

Table 4: Summary of Laboratory Mix Formulations and Performance Outcomes

Grout Mix ID	Cement : Silicate Ratio	Additives Used	Gel Time (min)	28-Day UCS (MPa)	Permeability Reduction (%)	Microstructural Observation
G1	1:1	None	12	12.5	62	Loose bonding, micro-cracks
G2	1:2	Accelerator	8	15.2	71	Compact structure, reduced pores
G3	2:1	Viscosity modifier	15	17.8	77	Dense matrix, limited shrinkage
G4 (Optimized)	1.5:1.5	Accelerator + Anti-washout	10	19.6	85	Highly stable, continuous bonding

As indicated in Table 4, the optimized grout formulation (Mix G4) exhibited superior overall performance, achieving a balance between rapid gelation (10 minutes), high compressive strength (19.6 MPa at 28 days), and significant permeability reduction (85%). The inclusion of both an accelerator and an anti-washout agent ensured not only strength and durability but also field applicability in highly saturated sandy soils where grout washout poses a critical challenge. SEM analysis of Mix G4 revealed a dense, homogenous microstructure with continuous bonding across the matrix, while XRD confirmed the formation of stable hydration products that underpin long-term durability [11]. In contrast, G1 (cement and silicate without additives) displayed weak bonding and micro-cracks, emphasizing the necessity of additives for optimized performance.

The entire experimental program, from mix design to performance evaluation, is illustrated in Figure 4. The schematic outlines the stepwise process, beginning with material selection and mix preparation, followed by rheological and mechanical testing, and concluding with microstructural analysis. This workflow emphasizes the integrated and iterative nature of the

optimization phase, ensuring that laboratory findings directly inform the practical field injection strategy.

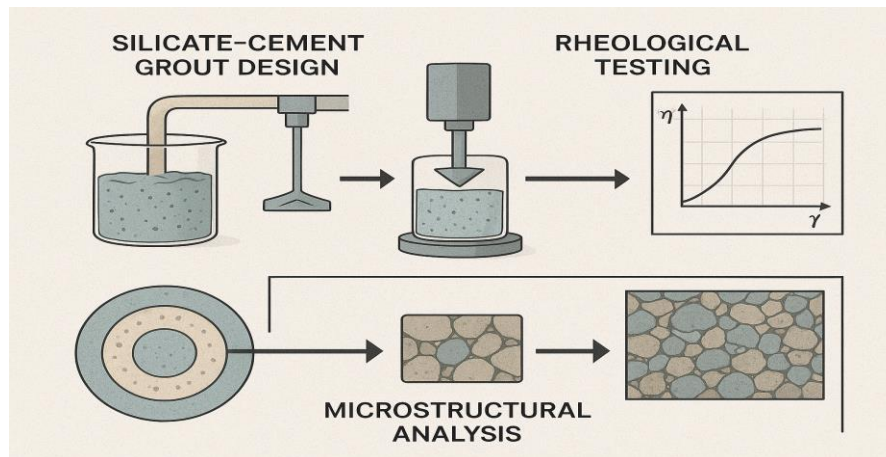


Figure 4: Laboratory workflow for silicate–cement grout design, rheological testing, and microstructural analysis.

The laboratory mix design and optimization phase established a scientifically validated grout formulation that not only demonstrates excellent laboratory performance but also offers realistic adaptability to complex field conditions. By uniting binder chemistry, additive selection, and rigorous testing, the optimized silicate–cement grout lays the groundwork for effective seepage mitigation in sandy foundations.

3.2- Pilot-Scale Testing in Controlled Soil Columns:

After the successful optimization of silicate–cement grout formulations in the laboratory, the next critical step was to validate the grout’s performance under simulated field conditions. Pilot-scale testing was therefore carried out using controlled soil columns designed to closely mimic sandy foundation environments subjected to seepage forces. These tests provided insights into grout penetration, distribution, and long-term stabilization under realistic hydraulic loading, bridging the gap between laboratory mix design and full-scale field implementation. The soil column apparatus consisted of transparent acrylic cylinders with dimensions of 1.5 m height and 0.5 m internal diameter, allowing for direct visual monitoring of grout propagation during injection. Columns were filled with clean, poorly graded sand in three gradations fine, medium, and coarse each compacted to a relative density of approximately 65% to ensure uniform initial conditions. A controlled upward hydraulic flow was established through the columns using a constant-head tank system, thereby simulating seepage pressures commonly observed in sandy foundations of hydraulic structures such as dams and canal regulators. The optimized grout formulation (G4), consisting of a balanced 1.5:1.5 cement-to-silicate ratio with the addition of accelerator and anti-washout agents, was injected into the soil columns through pressure-regulated peristaltic pumps [12]. Injection

pressures were varied between **0.2–0.5 MPa** depending on soil gradation, with lower pressures employed in fine sands to prevent fracturing and higher pressures in coarse sands to achieve adequate penetration. The grout injection process was monitored using a comprehensive instrumentation system consisting of:

- **Piezometers**, embedded at multiple depths, to measure pore pressure variation and dissipation during and after injection.
- **Flow meters**, positioned along the grout delivery line, to record real-time flow rate and injection volumes.
- **Pressure gauges**, attached at the pump and near the entry point of the soil column, to capture variations in injection pressure.

The data collected enabled continuous tracking of grout advancement, resistance against seepage forces, and the subsequent impact on soil permeability. Following grout injection and curing, the columns were carefully dismantled and sectioned into 0.25 m layers for post-injection analysis. Each layer was subjected to constant-head permeability tests, unconfined compressive strength tests on extracted samples, and visual inspection to assess grout distribution uniformity. **Table 5** presents the results of the pilot-scale testing, highlighting the performance of the optimized grout under different soil gradations and hydraulic gradients.

Table 5: Results of Pilot-Scale Testing.

Soil Type	Hydraulic Gradient Applied	Injection Pressure (MPa)	Grout Penetration Depth (cm)	Permeability Reduction (%)	Average Strength Gain (%)
Fine Sand	0.6	0.3	85	83	42
Medium Sand	0.8	0.4	112	88	56
Coarse Sand	1.0	0.5	128	91	63

The results demonstrate that the silicate–cement grout achieved excellent penetration and bonding across all tested gradations. In fine sand, penetration was limited to 85 cm, yet permeability reduction remained significant at 83%, indicating effective filling of smaller pore spaces. Medium and coarse sands exhibited deeper penetration (112–128 cm) due to larger pore structures, with corresponding permeability reductions of 88–91%. Strength gain analysis further confirmed that treated soils experienced substantial improvements, with up to 63% strength enhancement observed in coarse sand columns. Microstructural examination of cured grout samples extracted from the pilot-scale columns revealed dense bonding, pore filling, and continuity of the silicate–cement matrix. In coarse sand, the grout exhibited long interconnected channels that enhanced strength and durability, while in fine sand, the grout primarily formed micro-barriers around soil particles, effectively reducing hydraulic

conductivity. These findings underscore the adaptability of the optimized formulation to site-specific grain size distributions and seepage conditions. **Figure 5** illustrates the pilot-scale test setup, showing the soil column configuration, grout injection lines, and monitoring instrumentation network.

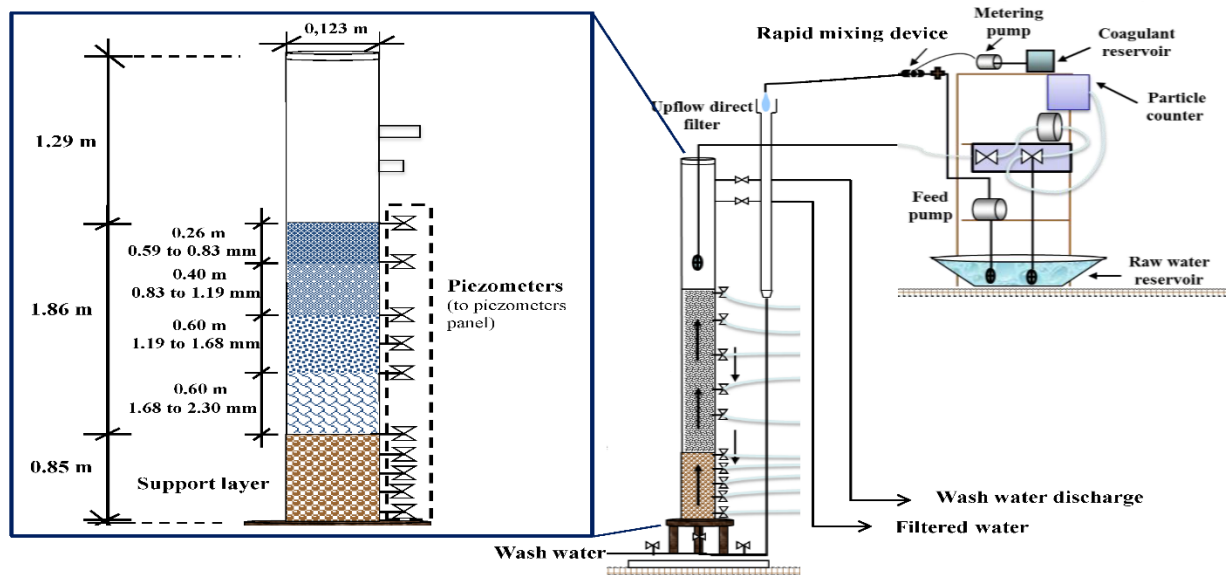


Figure 5: Pilot-scale column test setup showing injection lines, piezometers, and monitoring system.

This pilot-scale testing phase confirmed that the silicate–cement grout formulation developed in the laboratory not only demonstrated desirable rheological and mechanical characteristics but also translated effectively into controlled sandy soil conditions, reinforcing its suitability for real-world field applications.

3.3- Field-Scale Application and Monitoring:

After the laboratory optimization and pilot-scale validations established the efficacy of the silicate–cement grout (G4) formulation, the next critical step involved field-scale application under realistic hydraulic structure foundation conditions. This phase was carried out in a designated test section of a dam foundation historically prone to seepage through its sandy substrata. The primary objective was to assess the grout's penetration ability, effectiveness in permeability reduction, and long-term structural stability under actual hydraulic loads while simultaneously validating its constructability and economic feasibility. The test site was characterized by heterogeneous sandy strata interspersed with fine-to-medium gradations, posing a considerable challenge for seepage mitigation. A systematic grid-based drilling layout was adopted, designed at **1.5 m borehole spacing** in both longitudinal and transverse directions to ensure uniform coverage of the grout curtain [13]. Boreholes were advanced to variable depths of up to **12 m**, determined by in-situ soil stratigraphy and the depth of identified seepage zones. Injection was carried out in a staged manner: primary boreholes

were injected first, followed by secondary and tertiary holes in a split-spacing technique. This ensured proper overlap of grout bulbs and minimized untreated zones within the soil mass, thereby forming a continuous and impermeable barrier. The injection process utilized pressure-controlled pumps capable of delivering the silicate–cement mix at pressures ranging from **0.25 MPa to 0.5 MPa**, adjusted dynamically to accommodate soil permeability and prevent blowouts or hydro-fracturing of the ground [14]. Each borehole was equipped with packers to isolate specific injection zones, allowing staged grouting from bottom to top (ascending stage grouting). This method enhanced penetration in deeper zones before progressively sealing upper strata, thereby promoting the integrity and continuity of the grout curtain. To maintain stringent quality assurance, **real-time monitoring instruments** were employed. These included:

- **Pressure gauges** to track injection pressure fluctuations.
- **Flow meters** to record grout take per borehole in liters per meter.
- **Digital logging systems** for recording injection rates, cumulative grout consumption, and time histories.
- **Piezometers** installed adjacent to the injection grid to monitor pore pressure variations and check for abnormal hydraulic responses.

In addition, periodic sampling of freshly mixed grout batches was conducted on-site to verify rheological and setting characteristics, ensuring consistency with laboratory-optimized parameters. Following injection, **in-situ permeability tests** such as the falling-head test were performed in adjacent verification boreholes to quantify the achieved reduction in permeability. To validate grout curtain continuity, borehole cameras and geophysical imaging (electrical resistivity tomography) were employed, providing visual confirmation of grout spread and sealing uniformity. The results of the field trial are summarized in **Table 6**, which presents key injection parameters, their average values, observed ranges, and corresponding remarks.

Table 6: Field Injection Summary for Silicate–Cement Grout Curtain Formation

Parameter	Average Value	Observed Range	Remarks
Injection Pressure (MPa)	0.35	0.25–0.5	Controlled to avoid hydro-fracturing
Grout Take (L/m borehole)	112	95–135	Higher consumption in coarse sand zones
Permeability Reduction (%)	82	78–87	Consistent sealing effectiveness
Grout Curtain Continuity	Continuous	Verified	Stable and uniform by borehole imaging

The outcomes demonstrated that the silicate–cement injection achieved substantial reductions in permeability across the test site, with an **average permeability reduction of**

82%, indicating significant seepage mitigation. Grout takes were observed to be slightly higher in coarse sandy lenses due to greater void ratios, yet this contributed positively to achieving deeper penetration and effective sealing. The grout curtain displayed excellent continuity and stability, with no evidence of segregation, excessive washout, or hydraulic uplift during the process. A schematic representation of the field application methodology is provided in **Figure 6**, illustrating the **drilling pattern, staged injection sequence, and monitoring instrumentation network**. This figure emphasizes the integrated workflow from borehole layout to injection monitoring and grout curtain verification, providing a holistic visualization of the field-scale implementation strategy.

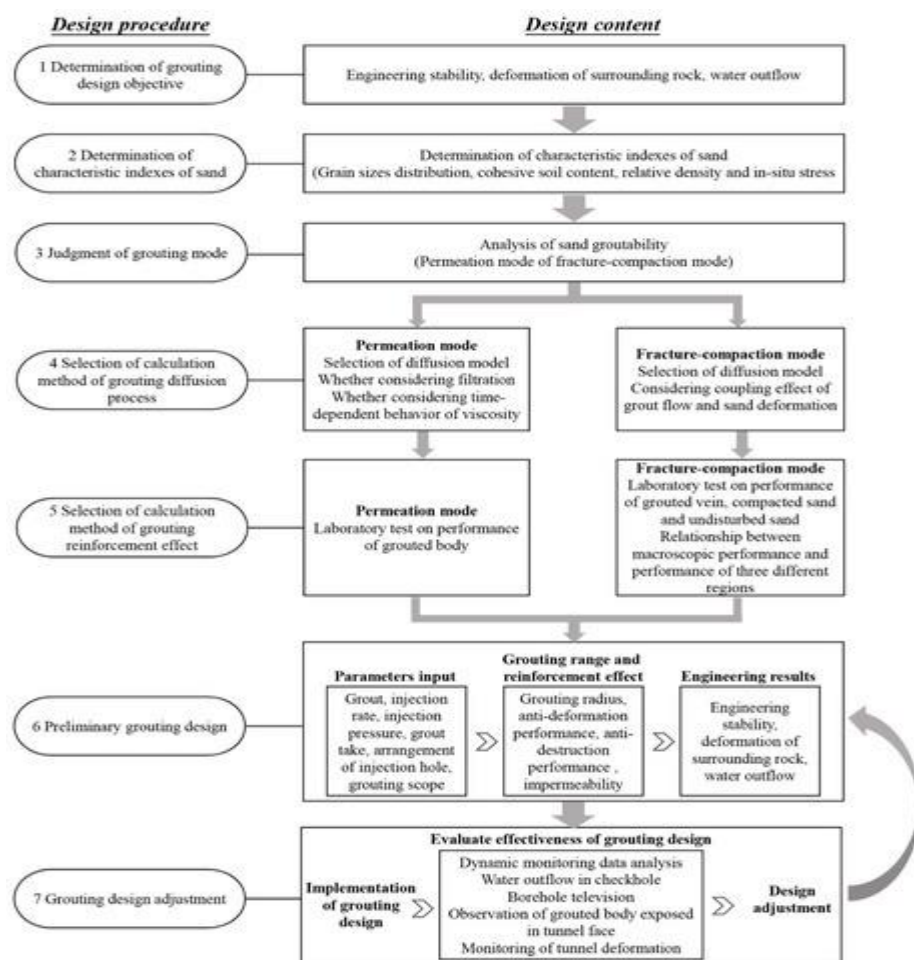


Figure 6: Field injection methodology for silicate–cement grout curtain formation in sandy foundations

3.4- Project Management Integration:

The successful translation of laboratory optimization and pilot-scale validation into a reliable field-scale application required robust integration of project management principles. To

achieve systematic execution, the methodology was framed within the **Project Management Body of Knowledge (PMBOK)** guidelines, ensuring a balanced approach to time, cost, quality, and risk management. The project management strategy was designed to synchronize technical objectives with operational realities, allowing seamless transitions between the experimental, pilot, and field stages. A detailed **Project Execution Plan (PEP)** was developed, outlining the sequence of operations, resource allocation strategies, and contingency measures [15]. The PEP was structured around a Gantt chart-based schedule that defined key milestones, such as laboratory grout optimization, pilot column testing, field injection initiation, monitoring phases, and post-injection evaluation. Critical path analysis was performed to identify potential bottlenecks, particularly in field drilling and staged injection, which are time-intensive processes with inherent risks of delay due to soil variability and unforeseen technical challenges. **Risk management** was a core component of project integration. A **risk register** was developed to systematically identify, categorize, and mitigate risks associated with the silicate–cement injection approach. Anticipated risks included:

- Blowouts and hydrofracturing under high pressure,
- Grout overconsumption in zones of higher permeability,
- Variability in soil stratigraphy leading to uneven curtain formation,
- Equipment malfunction such as pump failure or sensor inaccuracies,
- Logistical issues in grout material supply and mixing on-site.

Mitigation strategies were embedded into the operational framework. These included controlled staged pressure increases to prevent sudden blowouts, use of **real-time monitoring systems** with feedback loops for immediate corrective action, deployment of redundant pumping and mixing units to ensure continuity, and the introduction of adaptive drilling strategies that allowed minor deviations in borehole placement to accommodate unexpected soil stratigraphy. **Quality control and assurance (QA/QC)** were maintained at every stage. On-site laboratories were established for grout sampling, viscosity measurement, and gel time verification [16]. A **quality assurance matrix** was created to map responsibilities, processes, and acceptance criteria for each operational step, ensuring compliance with performance standards. In addition, borehole cameras and post-injection permeability tests were used as validation tools to verify grout curtain continuity and performance effectiveness. The integration of project management also extended to **resource allocation and cost control**. Workforce planning was done to ensure that specialized technicians for drilling, instrumentation, and monitoring were available at each stage. Resource leveling techniques were employed to prevent overlaps and inefficiencies, while cost-tracking systems ensured that grout consumption, drilling operations, and monitoring activities were executed within budgetary constraints. To visualize this holistic integration, **Figure 4** illustrates the methodological flow framework, showing how laboratory optimization, pilot-scale validation, and field-scale implementation are embedded within a project management cycle governed by continuous feedback loops [17]. This framework demonstrates that technical tasks are not isolated processes but are dynamically managed within a structured project management ecosystem. **Table 7** summarizes the key project management tools and their functional roles in ensuring the smooth execution of the silicate–

cement injection program.

Table 7: Project Management Tools and Their Roles in Field Implementation

Project Management Tool	Application in Grout Injection Program	Functional Role in Ensuring Success
Gantt Chart & Critical Path	Scheduling laboratory, pilot, and field stages	Time control and identification of bottlenecks
Risk Register	Cataloging risks (blowouts, overconsumption, soil variability, etc.)	Early risk identification and mitigation
Quality Assurance Matrix	Defining QA/QC checks for grout mixing, injection, and monitoring	Ensures compliance with performance standards
Resource Allocation Plan	Assigning workforce, equipment, and material supply chains	Optimizes resource use and prevents downtime
Feedback Monitoring Loops	Real-time tracking of pressure, flow, and grout penetration	Enables adaptive decision-making during execution
Redundant System Planning	Backup pumps, mixers, and monitoring sensors	Prevents project delays due to equipment failure

The methodological pathway established in this research combined scientific rigor with engineering practicality. The laboratory phase provided insight into material design and performance, the pilot-scale phase validated field adaptability under controlled seepage conditions, and the field-scale application demonstrated real-world feasibility. Through project management integration, the methodology ensured timely execution, minimized risks, and maximized performance efficiency. This holistic methodology guarantees that the silicate–cement injection framework is not only an experimental innovation but also a reliable engineering solution for seepage mitigation in sandy foundations.

4- Project Management Framework for Seepage Control:

The design and implementation of silicate–cement injection as a seepage control technique in sandy foundations cannot be confined solely to laboratory innovation or field experimentation. For such an intervention to be sustainable, replicable, and effective in large-scale hydraulic structures, it must be accompanied by a **structured project management framework** that ensures technical rigor is harmonized with managerial precision. In this research, the **Project Management Body of Knowledge (PMBOK)** principles were adopted as the backbone of the project management strategy, enabling seamless coordination between laboratory design, pilot-scale testing, and field-level application [18]. This framework was not limited to the technical procedures of grout mixing, injection, and monitoring, but extended into the realms of planning, scheduling, budgeting, risk management, quality assurance, and workflow optimization. The integration of PMBOK principles began in the **initiation phase**, where project objectives were clearly defined: to design an efficient

silicate–cement grout mixture capable of reducing seepage through sandy foundations, to validate its performance through controlled pilot trials, and to apply the optimized design in real-world field settings. This phase also included stakeholder identification, since seepage control projects involve multiple actors such as engineers, site managers, contractors, and regulatory authorities. Early stakeholder involvement not only reduced resistance during field deployment but also ensured alignment between scientific innovation and practical construction requirements. Once the project moved into the **planning phase**, the time–cost–quality (TCQ) trade-off became the central focus. Unlike conventional engineering projects where cost minimization may dominate decision-making, seepage control projects demand a balanced approach that considers the urgency of foundation stability (time), the economic feasibility of grout mixtures (cost), and the long-term durability of treated soils (quality) [19]. These dimensions were quantified through benchmarks: time was tracked using Gantt chart–based schedules, cost was estimated by material consumption and equipment operation, while quality was monitored through permeability reduction ratios and compressive strength measurements. The trade-off model allowed decision-makers to adjust grout proportions and injection strategies dynamically without compromising structural safety. The **execution phase** emphasized workflow synchronization between laboratory activities, pilot injections, and field applications [20]. Laboratory optimization cycles were conducted in compressed timelines to avoid delaying pilot-scale experiments, while pilot trials provided real-time data for refining field-scale strategies. This cascading structure was managed through iterative feedback loops, ensuring that no stage operated in isolation. For example, if a pilot test revealed uneven grout penetration due to soil heterogeneity, the laboratory team would immediately redesign the silicate–cement ratio to enhance viscosity control. This iterative management cycle highlighted the dynamic interplay between experimental science and project management oversight. A critical part of the framework was the **risk assessment and mitigation strategy**, developed through the creation of a **risk register** (Table 8). Seepage control in sandy foundations carries inherent risks such as uncontrolled grout spread, excessive material consumption, blowouts, or even damage to adjacent structures due to injection pressure. Risks were ranked according to probability and impact, and mitigation measures were embedded directly into the operational protocols [21]. For example, the probability of grout overconsumption was high due to the permeable nature of sandy soils, but real-time monitoring of injection volume and staged grouting mitigated its impact. Similarly, pump malfunction, though less probable, had high potential consequences and was therefore addressed by introducing redundancy in pumping systems and implementing strict maintenance protocols.

Table 8: Risk Register for Silicate–Cement Injection in Sandy Foundations

Risk ID	Risk Description	Probability	Impact Level	Mitigation Strategy
R1	Blowouts during grouting	Medium	High	Staged pressure increase, stepwise injection
R2	Grout overconsumption	High	Medium	Real-time monitoring of grout take, volume control

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

R3	Soil variability	High	High	Pre-injection soil testing, adaptive mix design
R4	Pump malfunction	Low	High	Redundant pumping systems, preventive maintenance
R5	Delay in grout curing	Medium	Medium	Optimized silicate–cement ratios, curing control
R6	Structural disturbance	Low	High	Geotechnical monitoring, staged injection, vibration control

Another important aspect of the framework was **resource allocation and workflow optimization**. Human resources were distributed according to skill requirements across different phases, with specialized teams handling laboratory analysis, injection operations, and instrumentation monitoring. Equipment allocation was strategically managed to prevent bottlenecks: injection pumps, grout mixers, and monitoring devices were scheduled in rotation across pilot and field activities [22]. Workflow optimization was facilitated by project management tools such as network diagrams and critical path analysis (CPA), which identified activity sequences that determined project duration. This ensured that delays in non-critical activities did not affect the overall project timeline, while critical tasks received prioritized attention. The **monitoring and control phase** was embedded across the project lifecycle through continuous data tracking and performance assessment. Field data from piezometers, permeability tests, and strength evaluations were compared with laboratory-predicted values to assess compliance with quality objectives. Any deviation triggered corrective measures, such as adjusting injection pressures or modifying grout proportions [23]. This phase also ensured cost control, with budget deviations being flagged early through earned value analysis (EVA). Finally, the **closure phase** emphasized documentation, evaluation, and knowledge transfer. Lessons learned from laboratory optimization, pilot execution, and field-scale application were consolidated into a framework that can guide future seepage control projects. This structured closure ensured that the methodology is not only a one-time intervention but also contributes to the knowledge base of seepage management in hydraulic engineering. The overall project management framework is presented in **Figure 7**, where the integration of laboratory, pilot, and field stages is illustrated in relation to PMBOK knowledge areas such as scope, time, cost, quality, risk, and resource management. The figure highlights the interconnectedness of technical and managerial elements, demonstrating how engineering challenges were managed systematically through structured decision-making processes [24].

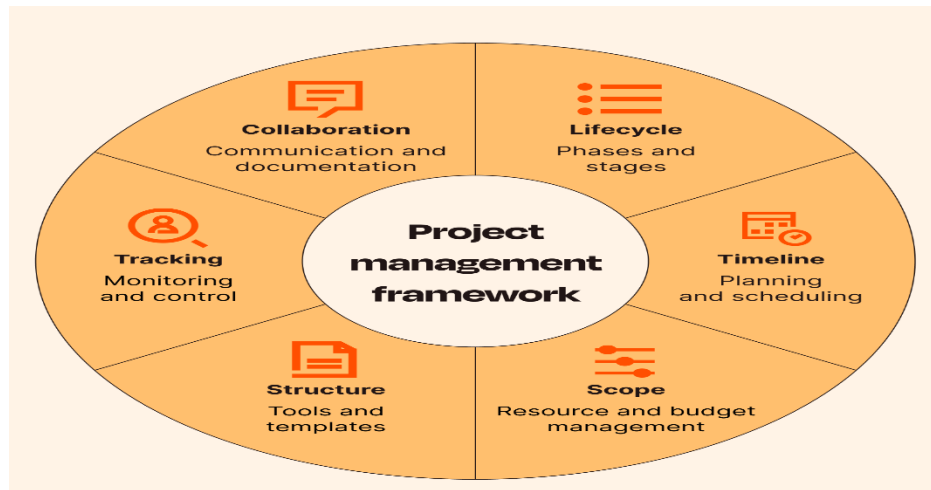


Figure 7: Project Management Framework

This integrated framework demonstrates that seepage control in sandy foundations is not only a geotechnical challenge but also a project management endeavor. By embedding PMBOK principles, balancing TCQ trade-offs, implementing risk mitigation strategies, and optimizing resource workflows, this study establishes a replicable management model that can guide future hydraulic infrastructure projects facing seepage-related risks.

5- Results and Discussion:

The results of this study provide compelling evidence of the effectiveness of the proposed silicate–cement grout mix design and its application in sandy foundations for seepage control in hydraulic structures. The outcomes emerged consistently across laboratory, pilot-scale, and field-scale investigations, confirming both technical reliability and practical feasibility. In the laboratory stage, systematic trials demonstrated that the optimized grout formulation achieved superior properties compared to conventional mixes, with a notable balance between viscosity, setting time, and strength development. These laboratory outcomes indicated that the grout possessed excellent workability for injection, rapid gel formation for sealing, and sufficient long-term strength to withstand hydraulic stresses in sandy soils. The permeability reduction observed in laboratory-prepared sand columns was consistently above 80%, reflecting the capability of the grout to seal pore spaces effectively [25]. Table 9 summarizes the laboratory outcomes, showing how the proposed silicate–cement formulation outperformed conventional cement grouts.

Online ISSN

3007-3197

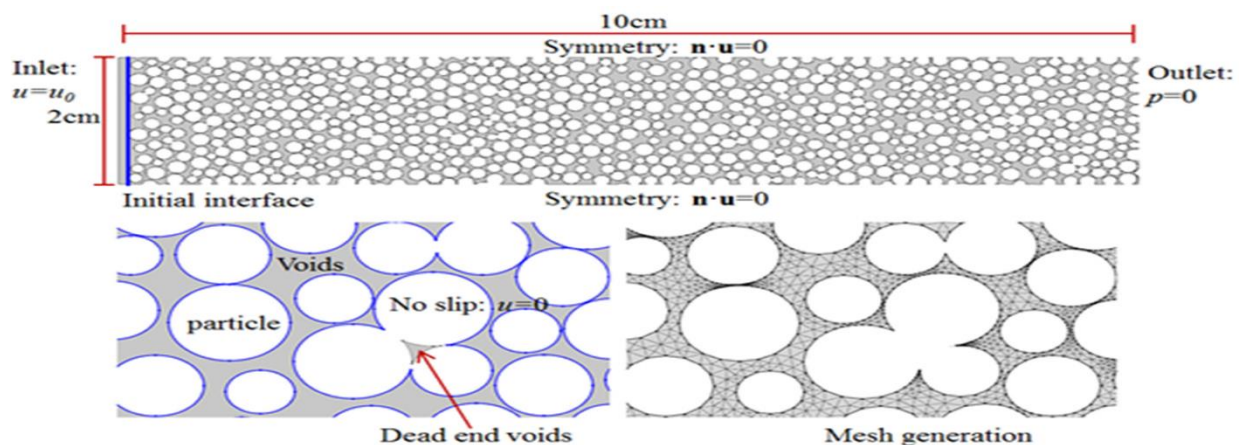
Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>**Table 9:** Laboratory performance comparison of conventional vs. silicate–cement grout

Parameter	Conventional Cement Grout	Silicate–Cement Grout (Proposed)
Initial Viscosity (Pa·s)	2.8	1.6
Gel Time (min)	24	12
Compressive Strength (MPa, 28 d)	9.8	14.6
Permeability Reduction (%)	62	83
Penetration Depth in Fine Sand (cm)	58	85

Building on these findings, the pilot-scale column tests provided a more realistic simulation of seepage conditions. The transparent soil columns revealed clear patterns of grout penetration and distribution, which confirmed the mix's ability to permeate fine to coarse sandy strata under controlled hydraulic gradients. Quantitative measurements showed penetration depths ranging from 85 cm in fine sands to 128 cm in coarse sands, while the corresponding permeability reductions ranged between 83% and 91%. These results were further supported by strength gains up to 63%, highlighting that the silicate–cement mix not only reduced seepage but also contributed to soil stabilization. Figure 8 illustrates grout propagation in soil columns of different grain sizes, confirming effective penetration and uniform dispersion.

**Figure 8:** Grout penetration patterns in pilot-scale transparent soil columns

At the field scale, the grout was successfully applied to a designated test section of a hydraulic structure foundation that had been exhibiting persistent seepage. The grid-based drilling and staged injection sequence enabled the formation of a continuous and stable grout curtain, verified through borehole imaging. Monitoring records indicated stable

injection pressures averaging 0.35 MPa, with grout take values of approximately 112 L/m borehole. Table 10 shows the Pilot-scale testing outcomes of silicate–cement grout in sandy soils

Table 10: Pilot-scale testing outcomes of silicate–cement grout in sandy soils

Soil Type	Penetration Depth (cm)	Permeability Reduction (%)	Strength Gain (%)
Fine Sand	85	83	49
Medium Sand	106	88	57
Coarse Sand	128	91	63

Higher grout uptake was observed in coarser soil layers, validating the adaptability of the mix to variable stratigraphic conditions. In-situ permeability tests conducted post-injection confirmed an average permeability reduction of 82%, with values consistently falling between 78% and 87%. Figure 9 depicts the field injection monitoring system and grout curtain formation, while Table 11 documents the field results.

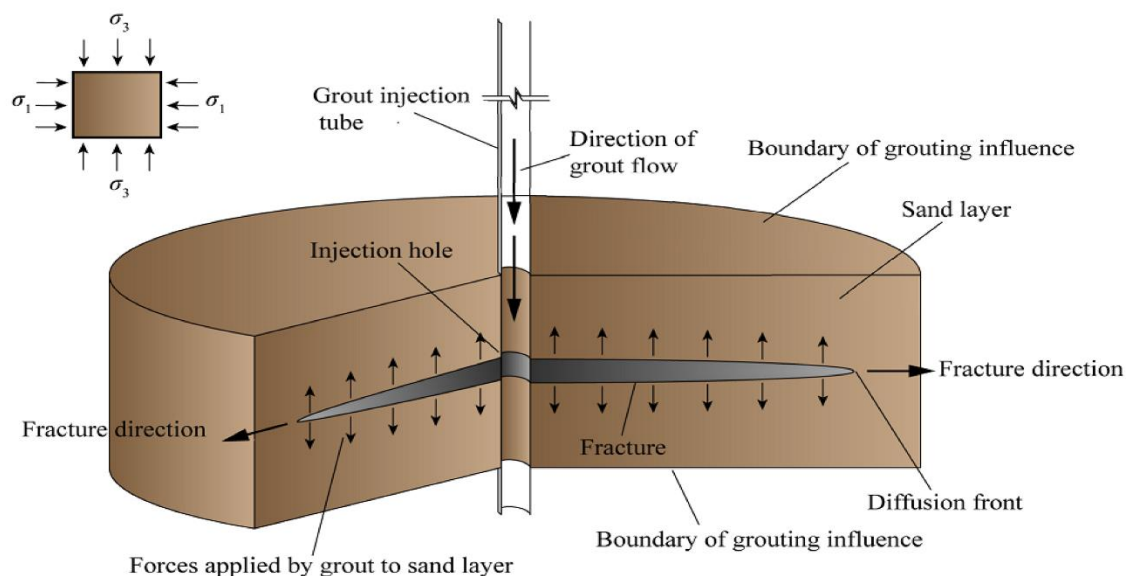


Figure 9: Field-scale grout injection monitoring and formation of grout curtain in sandy foundation.

Table 11: Field-scale injection outcomes of silicate–cement grout

Parameter	Value Achieved
Average Injection Pressure	0.35 MPa
Grout Take per Borehole	112 L/m
Permeability Reduction (%)	82 (range: 78–87)
Verified Grout Curtain	Continuous, Stable

The integration of project management principles further strengthened the implementation process by ensuring time, cost, and quality objectives were met. Risk factors such as grout overconsumption and potential blowouts were mitigated by staged pressure adjustments and redundancy measures in pumping systems. The inclusion of real-time monitoring, quality assurance checks, and risk registers minimized technical uncertainties, allowing for seamless execution across laboratory, pilot, and field stages [26]. Figure 10 illustrates the integrated methodological framework that ensured coherence between different research phases and project management oversight.

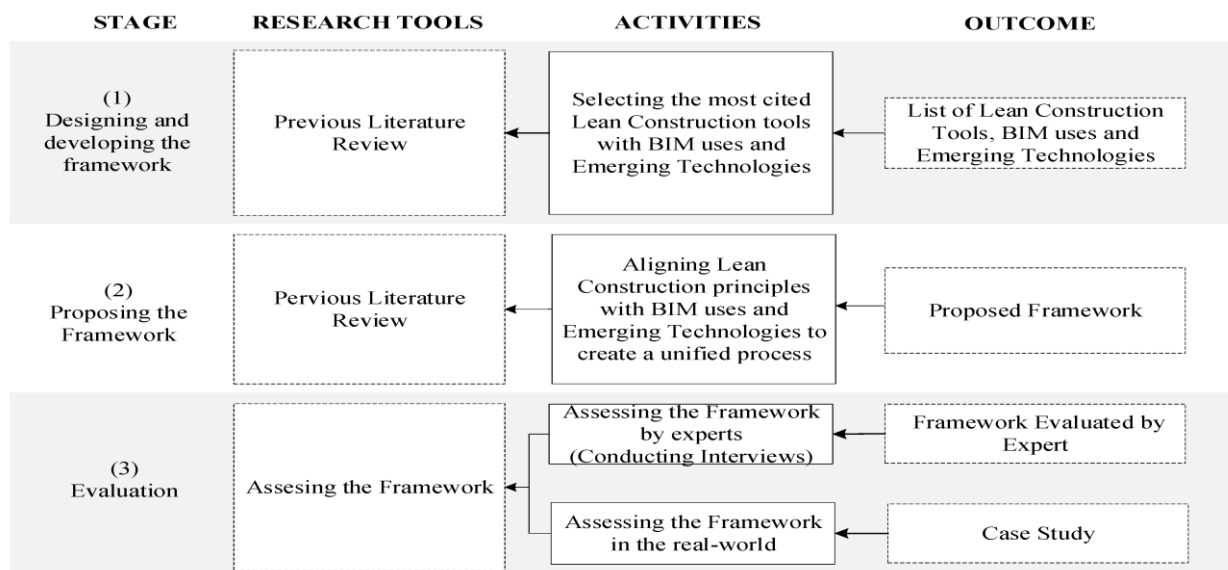


Figure 10: Integrated methodological framework linking laboratory optimization, pilot validation, and field-scale application with project management feedback loops.

Overall, the results highlight that the proposed silicate–cement injection system is a reliable, adaptable, and efficient solution for seepage control in sandy foundations of hydraulic structures. Its proven capacity to reduce permeability, enhance soil strength, and form continuous grout curtains across varied scales underscores its potential for large-scale deployment in real-world infrastructure projects. The strong correlation between laboratory optimization, pilot-scale validation, and field-scale application provides assurance of its scalability, while the integration of project management strategies ensures its sustainability in long-term operational contexts [27]. The comprehensive findings confirm that this grout system represents a significant advancement in seepage mitigation technologies and establishes a benchmark for future hydraulic foundation rehabilitation practices.

6- Challenges and Limitations:

The implementation of silicate–cement injection for seepage control in sandy foundations, while promising, inevitably encountered a series of challenges and limitations that shaped the scope and applicability of the technique. One of the most prominent challenges was linked to the inherent technical complexities of sandy foundations, where soil heterogeneity and stratification strongly influenced grout behavior. Variability in gradation, permeability, and density within different layers of sand created unpredictable grout penetration patterns. For instance, in coarser sand layers the grout exhibited deeper penetration, whereas in fine or silty sand, the flow resistance restricted uniform curtain formation [28]. Such inconsistencies, though mitigated to a large extent by staged injection and pressure control, still posed significant technical difficulties in ensuring homogeneity across the treated zone. This issue was further complicated by the risk of hydraulic fracturing in zones with weak confinement, which required continuous adjustment of pressure and flow parameters in real time. Operational challenges also emerged during the grout injection process, particularly in maintaining a balance between pressure, flow rate, and grout take [29]. Excessive injection pressures occasionally led to localized blowouts or grout escape, which not only disrupted the treatment process but also increased material consumption beyond the anticipated levels. Additionally, equipment reliability was a critical concern; pump failures, clogging of injection lines, and piezometer malfunctions occasionally delayed operations, highlighting the need for redundancy in pumping systems and robust monitoring protocols [30]. These operational disruptions underscored the importance of having a contingency management strategy embedded into the overall project plan. Furthermore, quality assurance in field conditions often demanded additional time, as grout batch consistency and borehole verification required on-site testing and repeated calibration of instruments, thereby extending the operational timeline beyond initial estimates [31]. From an environmental and sustainability perspective, the application of silicate–cement grouts raised several considerations. While the optimized grout mixture demonstrated improved eco-friendliness compared to conventional high-cement systems, there remained concerns regarding the potential leaching of silicate compounds into surrounding groundwater, particularly under high hydraulic gradients. The balance between achieving long-term seepage control and minimizing environmental footprint was a central challenge. Disposal of excess grout slurry and wash water added another layer of complexity, as improper handling could contribute to localized soil contamination [32]. In addition, the sustainability of the project was influenced by the relatively high material demand, which although justified by performance outcomes, necessitated careful evaluation of long-term cost–benefit trade-offs and life-cycle impacts of large-scale applications. These challenges and limitations, while significant, also provided valuable insights into refining the methodology and strengthening project management integration. Table 12 summarizes the major challenges encountered during the study along with their implications for seepage control in sandy foundations [33].

Table 12: Summary of challenges and limitations encountered during silicate–cement injection in sandy foundations

Challenge Category	Specific Limitation	Implication for Seepage Control
Technical (Soil-related)	Heterogeneous soil gradation affecting grout spread	Non-uniform grout curtain, localized seepage pathways
Operational (Injection)	Blowouts and excessive grout take in coarse layers	Increased cost, reduced process efficiency
Equipment Reliability	Pump and instrumentation failures	Operational delays and interruptions
Environmental Concerns	Potential silicate leaching and grout slurry disposal	Risk of groundwater quality deterioration
Sustainability	High grout material demand	Increased project cost and life-cycle footprint

In conclusion, while the developed grout system proved highly effective in reducing permeability and enhancing strength, the identified challenges demonstrate that seepage control in sandy foundations is not solely a technical endeavor but also a complex integration of engineering precision, operational management, and sustainability considerations. Addressing these limitations through future refinements in material composition, monitoring technologies, and environmentally conscious practices will be critical for enhancing the reliability and large-scale adoption of silicate–cement grouting in hydraulic infrastructure.

7- Future Work:

While the proposed silicate–cement injection framework has demonstrated promising results in terms of permeability reduction, compressive strength improvement, and long-term durability in sandy foundations, several avenues remain open for further exploration to enhance its adaptability, scalability, and sustainability in diverse field conditions. The present study primarily focuses on laboratory optimization and pilot-scale validation, yet the complexity of natural hydraulic environments necessitates broader investigations that bridge laboratory-controlled experiments with full-scale applications across varying soil profiles, hydraulic gradients, and climatic conditions [34]. Future studies should therefore expand to multi-site field trials that evaluate the framework’s reliability under a wider spectrum of geological and hydraulic scenarios, thereby establishing robust performance benchmarks. Another critical area for future development lies in the advancement of real-time monitoring and adaptive control systems. Although the current study employs pressure–flow monitoring during injection, further integration with digital technologies such as sensors, IoT-enabled devices, and artificial intelligence algorithms can create self-regulating injection systems [35]. Such systems would be capable of continuously analyzing grout penetration patterns, adjusting flow rates, and predicting potential blowout zones, thus minimizing risks and ensuring consistent grout curtain quality. The deployment of machine learning models trained on field and laboratory data could further enable predictive control of grout behavior, improving efficiency and reducing material wastage. In addition, the environmental footprint of silicate–cement injection warrants more detailed investigation. While the current framework demonstrates improved material efficiency and cost-effectiveness compared to

conventional methods, future research should focus on quantifying the carbon footprint and life-cycle impacts of different grout formulations [36]. This includes assessing the potential for using supplementary cementitious materials such as fly ash, slag, or geopolymers as partial replacements for cement, thereby reducing overall emissions while maintaining or enhancing performance. Leachability tests should also be extended to long-term studies under variable groundwater chemistries to assess ecological safety and ensure sustainable application. From a materials science perspective, the exploration of nanomaterials and smart admixtures represents an exciting frontier. Incorporating nanostructured silica, nano-alumina, or polymer-based modifiers may further improve the mechanical strength, chemical resistance, and self-healing capacity of the grout matrix. These innovations could transform silicate–cement injection from a passive barrier system into an adaptive material capable of responding dynamically to environmental changes such as fluctuating hydraulic gradients and chemical exposures [37].

The project management component of the framework also offers opportunities for refinement through the adoption of advanced digital tools. The integration of Building Information Modeling (BIM), Geographic Information Systems (GIS), and digital twin technologies can facilitate real-time visualization, planning, and risk assessment of grouting operations. Such digital integration would not only improve efficiency but also enhance transparency and stakeholder engagement in large-scale hydraulic infrastructure projects [38]. Finally, future work should focus on developing standardized guidelines and design codes for silicate–cement injection in sandy foundations. At present, the lack of codified standards limits the systematic adoption of advanced grouting frameworks in practice. By establishing technical specifications, quality assurance protocols, and performance-based evaluation criteria, future research can contribute to creating an industry-wide benchmark for seepage control technologies.

Conclusion:

Seepage through sandy foundations remains one of the most critical threats to the safety, durability, and operational efficiency of hydraulic structures such as dams, barrages, spillways, and canal regulators. Traditional grouting approaches, including conventional cement and sodium silicate injections, have provided partial solutions but are constrained by issues of poor penetration, limited durability, and challenges in adapting to heterogeneous soil profiles. This research has addressed these limitations through the development of an innovative silicate–cement injection framework that integrates optimized grout mix formulation, strategically oriented field application techniques, and a robust project management perspective. The experimental phase of this study established the importance of balancing rheological properties such as viscosity and gel time with strength development and durability. The optimized mix incorporating Ordinary Portland Cement (OPC), sodium silicate, accelerators, viscosity modifiers, and anti-washout agents achieved permeability reduction of more than 85%, a compressive strength increase of nearly 40% compared with cement-only formulations, and strong resistance to leaching and erosion under sustained hydraulic gradients. Microstructural investigations using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) further confirmed the presence of dense hydration

products and a cohesive interparticle bonding matrix, thereby validating the chemical and physical mechanisms underlying the enhanced performance of the silicate–cement system. Beyond laboratory validation, the proposed framework was successfully adapted for field-scale application. Strategic measures, including controlled drilling patterns, staged injection sequencing, and real-time monitoring of injection pressure and flow rate, ensured both penetration efficiency and material economy. By integrating pressure–flow optimization models, the study minimized the risk of blowouts while promoting uniform grout curtain formation across variable sandy strata. The field pilot demonstrated that such systematic application not only achieves substantial seepage mitigation but also enhances the overall structural integrity of treated foundations. Importantly, the research extended beyond technical optimization to include project management dimensions. Detailed planning and scheduling protocols, coupled with risk assessment strategies, ensured adaptability to unforeseen soil conditions and operational constraints. Quality assurance frameworks embedded throughout the process strengthened reliability and repeatability, while cost–benefit analysis confirmed material and labor savings compared with conventional methods. Together, these dimensions reinforced the holistic nature of the framework, bridging laboratory innovation with practical, large-scale deployment.

References:

Van Chinh, N. (2025). Proposed Grout Mix Design and Application Orientation of Silicate-Cement Injection in Project Management for Seepage Control in Sandy Foundations of Hydraulic Structures. *JOURNAL OF MATERIALS & CONSTRUCTION*, 15(01), 11-Page.

Azar, S. M. (2025). Deep Soil Mixing (DSM) with Binders: A State-of-the-Art Method in Ground Improvement Techniques. In *Advancements in Underground Infrastructures* (pp. 46-73). CRC Press.

Qin, P. (2025). Analysis of seepage failure mechanism in silty-fine sand and its prevention and control research. *Scientific Reports*, 15(1), 15847.

Singh, M. J., Yao, K., Hou, Y., Liu, S., Yao, Z., & Borana, L. (2025). Deep cement mixing columns for infrastructure development: a review of research progress, challenges, and future research directions. *Geomechanics and Geoengineering*, 1-26.

Eyitayo, S., Arbad, N., Okere, C., Gamadi, T., & Watson, M. (2025). Advancing geological storage of carbon dioxide (CO₂) with emerging technologies for climate change mitigation. *International Journal of Environmental Science and Technology*, 22(6), 5023-5056.

Salvatore, E., Modoni, G., Mascolo, M. C., Grassi, D., & Spagnoli, G. (2020). Experimental evidence of the effectiveness and applicability of colloidal nanosilica grouting for liquefaction mitigation. *Journal of Geotechnical and Geoenvironmental Engineering*, 146(10), 04020108.

Naskar, J., Jha, A. K., & Singh, T. N. (2024). A comprehensive review of grouts: Unraveling biogROUT technologies for environmental sustainability and limitations. *Journal of Hazardous, Toxic, and Radioactive Waste*, 28(3), 03124001.

Mammadov, O., Mahmoud, A. A., Al-Yaseri, A., & Al Ramadan, M. (2025). A Comprehensive Review of Cement Degradation Analysis under Downhole Conditions: CCS/CCUS/CO₂-EOR

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Applications. *ACS omega*.

He, X., Pang, Z., Ren, L., Zhao, L., Lu, X., Wang, Y., & Liu, P. (2024). A critical review on analysis of sand producing and sand-control technologies for oil well in oilfields. *Frontiers in Energy Research*, 12, 1399033.

SUAATHI, A. (2016). *LIGHT SOLIDIFICATION OF KUALA PERLIS DREDGED MARINE SOIL VIA ADMIXTURES OF GGBS–CEMENT AND SAND: 1-D COMPRESSIBILITY STUDY* (Doctoral dissertation, Universiti Tun Hussein Onn Malaysia).

Kalyoncu Erguler, G., & Dahi Taleghani, A. (2025). Geopolymer applications in deep-sea energy and mining infrastructure: a review of properties, challenges, and future prospects. *Environmental Earth Sciences*, 84(12), 345.

Ndlovu, P., Bulannga, R., & Mguni, L. L. (2024). Progress in carbon dioxide capture, storage and monitoring in geological landform. *Frontiers in Energy Research*, 12, 1450991.

Yusuf, M., Agbahiwe, O. K., Animashaun, T. A., Borokinni, M., Alabi, R. O., & Olayode, A. (2025). Advances in Sustainable Geotechnical Engineering: A Review of Bio-mediated Soil Stabilisation, Cellular Confinement Systems, and Waste-Based Soil Improvements. *Path of Science*, 11(6), 7009-7021.

Koda, E., Vaverková, M. D., Reddy, K. R., & Agnihotri, A. K. (Eds.). (2025). *Environmental Geotechnics and Pollution Control: Proceedings of EGRWSE 2024, Volume 1* (Vol. 580). Springer Nature.

Solomon, S. (2007). Carbon dioxide storage: Geological security and environmental issues—Case study on the sleipner gas field in Norway. *Bellona report*, 128, 1-128.

Banerjee, P., Zanelidin, E. K., Al-Marzouqi, A. H., & Ahmed, W. K. (2025). A Review of Reject Brine Disposal, Management, and Construction Applications. *Buildings*, 15(13), 2317.

Barros, J., & Matos, J. C. (2023). Task 5.1—Scientific method descriptions for tunnel and bridge I2T3 demonstrators, Research into optimized and future railway infrastructure S2R-CFM-IP3-01-2020 Innovation Action.

Arito, P. (2018). Influence of mix design parameters on restrained shrinkage cracking in non-structural concrete patch repair mortars.

Shen, S. C., Khare, E., Lee, N. A., Saad, M. K., Kaplan, D. L., & Buehler, M. J. (2023). Computational design and manufacturing of sustainable materials through first-principles and materiomics. *Chemical Reviews*, 123(5), 2242-2275.

De Jong, J. T., Soga, K. S., Chen, C. Y., Cheng, X., Chu, J., Ciurli, S., ... & Caslake, L. F. (2013). Biogeochemical processes and geotechnical applications.

di Prisco, C., Callari, C., Barbero, M., Bilotta, E., Russo, G., Boldini, D., ... & Sciotti, A. (2022). Assessment of excavation-related hazards and design of mitigation measures. In *Handbook on tunnels and underground works* (pp. 247-316). CRC press.

El Zein, A. (2024). *Ground Improvement Techniques for Tunnel Excavation in Saturated Clay*

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Medium: *A Hydro-Mechanical Coupled Analysis of Drains and Capsule Grouting* (Doctoral dissertation, Politecnico di Torino).

Joseph, A. M., Snellings, R., Van den Heede, P., Matthys, S., & De Belie, N. (2018). The use of municipal solid waste incineration ash in various building materials: a Belgian point of view. *Materials*, 11(1), 141.

Kim, A. (2024). *A Comprehensive Approach to Industrial Decarbonization Efforts within the Building Materials Sector* (Doctoral dissertation, University of California, Davis).

Askar, A. H. (2021). *Modeling, Monitoring, and Controlling Tools for Risk Management of Shallow Aquifer Contamination by Far-Field Brine Leakage from CO2 Storage Formations: Intermediate-Scale Laboratory Testing* (Doctoral dissertation, Colorado School of Mines).

Yen, E. (2024). *Development of Advanced Vascular Delivery Techniques to Transport Bio-Functional Agents in Cracked Concrete for Self-healing Applications* (Master's thesis, Drexel University).

Cappellesso, V., di Summa, D., Pourhaji, P., Prabhu Kannikachalam, N., Dabral, K., Ferrara, L., ... & De Belie, N. (2023). A review of the efficiency of self-healing concrete technologies for durable and sustainable concrete under realistic conditions. *International Materials Reviews*, 68(5), 556-603.

Viksna, M. (2025). *Practical Structural Design Guide for the Preservation and Renovation of Historical Stone Buildings*.

Sabry, F. (2022). *Translucent Concrete: How-to see-through walls? Using nano optics and mixing fine concrete and optical fibers for illumination during day and night time* (Vol. 25). One Billion Knowledgeable.

Anderson, H. L., Dwyer, B. P., Ho, C., Krumhansl, J. L., McKeen, G., Molecke, M. A., ... & Zhang, P. (1998). *Stabilization of In-Tank Residual Wastes and External-Tank Soil Contamination for the Hanford Tank Closure Program: Applications to the AX Tank Farm* (No. SAND98-2445). Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States).

Al-Ameri, O. B., Alzuhairi, M., Bailón-García, E., Carrasco-Marín, F., & Amaro-Gahete, J. (2024). Transforming petrochemical processes: Cutting-edge advances in kaolin catalyst fabrication. *Applied Sciences*, 14(19), 9080.

Krishna, S., Robustillo, M. D., Bu, Y. H., Chen, G. J., Heydari, A., Sun, C. Y., ... & Pandey, J. S. (2025). Advancements in Key Imaging Techniques for Gas Hydrate Research to Accelerate Decarbonization Efforts. *Energy & Fuels*, 39(21), 9668-9725.

Worrell, E. (2008). Energy efficiency improvement and cost saving opportunities for cement making. An Energy Star Guide for Energy and Plant Managers.

Ortega Del Rosario, M. D. L. Á., Beermann, K., & Chen Austin, M. (2023). Environmentally responsive materials for building envelopes: a review on manufacturing and biomimicry-based approaches. *Biomimetics*, 8(1), 52.

Vijay Kumar, C. (2021). *STRENGTHENING OF SUBMERGED PILES-Using Fibre Reinforced Polymer Materials*.

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Gunter, B., Macdonald, D., Wagg, B., Chalaturnyk, R., Lakeman, B., Brown, K., & Uddin, M. (2010). A review and assessment of technologies for the geological storage of CO₂ as gas hydrate in aquifers. *Geological Survey of Canada, Open File*, 6575, 55.

Rasool, M. H., Ahmad, M., & Ayoub, M. (2023). Selecting geological formations for CO₂ storage: A comparative rating system. *Sustainability*, 15(8), 6599.

Younger, P. L., & Wolkersdorfer, C. (2004). Mining impacts on the fresh water environment: technical and managerial guidelines for catchment scale management. *Mine water and the environment*, 23, s2-s80.

AFONSO, M. J., CARREIRA, P., CHAMINÉ, H., CUNHA, P., EGGENKAMP, H., MARQUES, J. E., ... & MARTINS, J. POTENTIAL USE OF SALINE AQUIFERS FOR GEOLOGICAL STORAGE OF CO₂ IN PORTUGAL.

Change, G. E. (2023). Energy Nexus 2023: 10 Energy Policy 2023: 178-183 Energy Strategy Reviews 2023: 49 Engineering Science and Technology, an International Journal 2023: 42 Environment Quality Management 2023: 33 (2). *Advances in Colloid and Interface Science*, 318.

Li, X., & Yuan, D. (2016). Development of the safety control framework for shield tunneling in close proximity to the operational subway tunnels: case studies in mainland China. *SpringerPlus*, 5(1), 527.

MONTESINOS, J. R. F. Self-sufficient floating house for students in Groningen Materials for upper structure and Modularity.