IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 23, Issue 5 Ser. I (Sep. – Oct. 2026), PP 01-08
www.iosrjournals.org

Multiscale Chemo-Physical Coupling in Sustainable Ground Improvement: A Review of Micro-Chemical Soil Stabilization and Macro-Dynamic Soil-Structure Interaction for Critical Infrastructure

Dipayan Sikder[1], Md. Maidul Islam[2], Md. Shojib Mia[2]
[1]*(Nuclear Safety Division, Bangladesh Atomic Energy Regulatory Authority, Dhaka, Bangladesh)*
[2]*(Nuclear Safeguards Division, Bangladesh Atomic Energy Regulatory Authority, Dhaka, Bangladesh)*

Abstract: *Geotechnical subgrade preparation for high consequence structures like nuclear power plants (NPPs) and Small Modular Reactors (SMRs) is one of the most challenging disciplines in civil engineering, because of the high structural loads, and safety margins, that are required. This review paper connects two traditionally separate fields: micro-scale material chemistry of sustainable soil stabilizers and macro-scale structural Soil-Structure-Foundation Interaction (SSFI) under dynamic seismic excitation. The critical, multiscale physical-chemical interface between these disciplines, Deep Soil Mixing (DSM), is evaluated. The pozzolanic and geo-polymeric gelation kinetics (forming calcium-silicate-hydrate and sodium/calcium-aluminate-silicate-hydrate frameworks) of eco-friendly binders are obtained from industrial and agricultural waste materials (e.g., coal fly ash, calcium carbide residue, ground granulated blast-furnace slag) at the material level. The issue of the suppression of sulfate-induced ettringite heave, which is a major weakness of conventional cement, and the mathematical normalization of geo-mechanical properties using Consoli's porosity/binder index has been discussed. We have studied geometrically nonlinear phenomena of SSFI (sliding, separation/gapping, rocking-induced uplift) and Structure-Soil-Structure Interaction (SSSI) in clustered nuclear islands at the structural level. Important is a basic chemo-physical tension: chemical optimization for maximum binder compressive strength increases subgrade shear wave velocity, which creates dynamic wave impedance contrasts that retain seismic energy and result in increased horizontal and vertical structural accelerations. Finally, we have reformulated this contact boundary in the light of Massimo Cacciari's philosophical dialectic between the open threshold and the rigid boundary, showing that it is physically necessary to model the contact boundary as an unbonded contact boundary with Kuhn-Tucker unilateral constraints, in order to capture the floor response spectra that govern the critical internal equipment. Primary research gaps and a roadmap towards unified chemo-dynamic modeling are presented.*
Key Words*: Sustainable Soil Stabilization, Deep Soil Mixing, Soil-Structure-Foundation Interaction, Alkali-Activated Geopolymers, Nuclear Geotechnical Safety.*

Date of Submission: 27-08-2026 Date of Acceptance: 06-09-2026

I. Introduction

Geotechnical site evaluation and subgrade engineering are fundamental aspects of nuclear safety, directly influencing the structure of Nuclear Power Plants (NPPs) and Small Modular Reactors (SMRs) under static and extreme dynamic loading conditions. Nuclear facilities have very high dead weights, high degree of structural embedment and stringent seismic safety margins to avoid catastrophic beyond-design-basis events [1, 2] as compared to typical civil infrastructure. Geotechnical risks are complex when the subgrade conditions are problematic, such as highly plastic clays, loose saturated sands or chemically unstable coastal deposits. These include excessive differential static settlement, bearing capacity failure, dynamic site amplification, and earthquake-induced soil liquefaction [3, 4]. The mitigation of these subsurface hazards should be undertaken using a comprehensive geotechnical approach that goes beyond the use of index tests and involves careful, multiscale physical and chemical testing.

Soil stabilization has progressed from the traditional trial-and-error physical modification (compaction or mechanical blending) to physicochemical subgrade engineering that is based on materials chemistry, chemical mineralogy, and thermodynamic equilibrium in modern nuclear geotechnics [5, 6]. Ground improvement protocols must meet strict regulatory guidelines (e.g., IAEA SSG-93, SSG-61 and USNRC NUREG-0800 Section 2.5.4) which require full site characterization, ongoing field monitoring, and extensive quality assurance programs [7]. The main structural engineering tool to achieve this stabilization is block-type Deep Soil Mixing

(DSM) and compact engineered backfills, which chemically stabilize the weak natural ground and create a high performance monolithic foundation support [2, 7].

This review paper connects two traditionally isolated fields in geotechnical engineering: the micro-scale materials chemistry of sustainable pozzolanic and geo-polymeric binders (Pillar I) and the macro-scale structural geodynamics of Soil-Structure Interaction (SSI) and Structure-Soil-Structure Interaction (SSSI) under seismic loading (Pillar II). These domains are synthesized, thus tackling the basic chemo-physical tensions in DSM. We have examined the effects of optimizing the chemical binders for compressive strength, which can have a counterproductive effect on the wave impedance of the site, resulting in localized energy focusing, resonant amplification of horizontal and vertical spectral accelerations, and foundation rocking with geometric gapping and uplift [2, 4]. Finally, we have transformed this mechanical separation into a formal mathematical contact representation, according to Massimo Cacciari's [1] philosophical dialectic of the threshold (limen) and the boundary (limes) and offer a new paradigm for critical facility design.

II. Chemo-Mineralogical Soil Stabilization Advances

High-calcium admixtures like Ordinary Portland Cement (OPC) and hydrated lime are traditionally used as chemical additives for the modification of clayey and expansive soils. These traditional stabilizers are very effective in ambient conditions but are extremely vulnerable from the environmental and technical aspects. The decarbonization of limestone and fossil-fuel intensive burning contribute around 8% to 10% of the global CO_2 emissions from OPC manufacturing alone [8]. From a mechanical point of view, the failure modes of cement treated soils are very brittle and the soils are very prone to microcracking. Most importantly, in sulfate-bearing clays, which are often found in coastal regions that are preferred for nuclear cooling water intake, the calcium based hydrated phases cause a catastrophic swelling and heave phenomenon called ettringite and thaumasite distress [8, 9].

Sulfate-induced Heave (Ettringite Distress) Chemistry:

The mixing of calcium-based stabilizers (lime or OPC) with sulfate bearing clays results in high alkalinity (pH > 12), which dissolves the clay minerals, releasing highly reactive amorphous alumina and silica. These soluble species react to form the highly expansive needle-like mineral ettringite [hydrous calcium aluminum sulfate: $Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$] in the presence of soluble sulfate ions (from groundwater or soil) and calcium [8, 9]. The chemical reaction is written as:

$$6Ca^{2+} + 2Al(OH)_4^{-} + 3SO_4^{2-} + 4OH^{-} + 26H_2O \rightarrow Ca_6[Al(OH)_6]_2(SO_4)_3 \cdot 26H_2O \quad (1)$$

The crystallization pressure produced by the extreme hydration-induced swelling of ettringite crystals on contact with water is more than 2-3 MPa. This pressure is significantly greater than the tensile strength of the stabilized soil and causes the microstructural disintegration, high macro-heaving and loss of bearing capacity [8, 9]. However ettringite, under lower temperature conditions (usually < 15 °C), and in the presence of carbonate sources can mineralogically transform to thaumasite [$Ca_3Si(OH)_6(CO_3)(SO_4)\cdot 12H_2O$] which directly attacks the calcium-silicate-hydrate (C-S-H) binder gel, converting the stabilized soil into a cohesionless mush [8].

Alternative as well as Sustainable Green Binders

Considering an environmental concern of carbon footprint associated with geotechnical activities, and to prevent sulfate heave, recent research on material has focused on cement-free, sustainable materials, which are produced using industrial, agricultural and domestic by-products. This circular economy strategy is targeted towards coal fly ash, class C and Class F (CFA), ground granulated blast-furnace slag (GGBS), ground glass, cement kiln dust (CKD) and calcium carbide residue (CCR) [6, 10, 11, 12]. Ground glass and Class F fly ash are highly active pozzolans that provide the silica and alumina that is required. CCR, a harmful domestic byproduct in acetylene gas production process, is a portlandite-rich [$Ca(OH)_2$] activator [6, 10]. The pozzolanic reactions work by the dissolved portlandite reacting with the amorphous silica and alumina inside the gels as they precipitate, resulting in the formation of stable Calcium-Silicate-Hydrate (C-S-H) and Calcium-Aluminate-Hydrate (C-A-H) gels, which encapsulate soil particles [10]. A $Ca/(SiO_2 + Al_2O_3)$ ratio of 1.5 yields the optimum chemical balance, maximizing unconfined compressive strength (UCS) and durability against wet/dry cycling, but with the microcracks appearing after long term exposures [13].

There is a potential to replace the use of alkali and its related environmental consequences by developing alkali-activated geo-polymerization and ettringite suppression. The sustainable ground stabilization is alkali-activated geo-polymerization. Geopolymers are produced by dissolving or activation of low calcium, high aluminosilicate materials (fly ash or metakaolin) with a high concentration alkaline solution, which is regularly made up of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) [14]. This chemical process has four identifiable kinetic stages:

(1) complete dissolution of the aluminosilicate minerals by the very high concentration hydroxyl ions;

(2) diffusion and reorganization of released silicate and aluminate monomers;

(3) chemical polycondensation of alkali metal cations (Na^+ or K^+) with these monomers, forming an amorphous, three-dimensional Sodium Aluminate Silicate Hydrate (N-A-S-H) gel framework; and

(4) mechanical hardening of the gel to bind soil aggregates together [14].

To speed up ambient temperature curing, GGBS is mixed to precipitate the coexisting network of calcium-aluminate-silicate-hydrate (C-A-S-H) gels, which can quickly improve the mechanical strength [14]. Most importantly, geopolymer inhibits the production of ettringite. The substitution of 60-80% of lime or OPC by GGBS ties up the available calcium in stable and non-expansive C-A-S-H gels and inhibits the mobility of alumina [9]. Geopolymer-treated clay exhibits excellent geo-mechanical and volumetric stability for long time (1 year) of immersion in high concentration (50 g/L) Na_2SO_4 and $MgSO_4$ solutions, with maximum volumetric changes of less than 1.2% that is far less than the usual structural failure of 10% [14]. The magnesium sulfate, however, is much different and more aggressive than sodium sulfate. The magnesium ion (Mg^{2+}) is hydrolysis and releases hydrogen ions which gradually acidify the pore solution [14]:

$$Mg^{2+} + 2H_2O \rightleftharpoons Mg(OH)_2(s) + 2H^+ \qquad (2)$$

This acidification will lower the high alkali content of the geopolymer matrix from its desirable (> 12) to 10.1 with Magnesium Sulfate while it is 10.6 with Sodium Sulfate and 11.2 with Tap water [14]. This localized pH reduction slows down the reaction kinetic gain, and leads to lower Peak of Unconfined Compressive Strength (q_u) and lower Stiffness Modulus (E_{50}) during the decadal life cycles of geo-polymerization, since the pH ≥ 12 must be maintained for continuous dissolution and polycondensation [14].

Geomechanical Normalization: Consoli's Porosity/Binder Index

Consoli et al. [10] presented a mathematical normalization procedure based on the porosity/binder index for a rational and scientific approach to the dosage of sustainable waste-binder blends. A rational model that shows the unconfined compressive strength (q_u) of stabilized soils depends on one single and governing physical index, which can be expressed as:

$$q_u = K \cdot [\ \eta / (B_{iv})^{\alpha}\ ]^{-a} \qquad (3)$$

where K is a scalar parameter (in kPa) and is unique to each particular soil-binder system and increases with curing time as the cementation process follows progress of the chemical cementation [10]. The index η denotes the porosity of compacted blend (%), B_{iv} denotes the volumetric content of binder in compacted blend (Binder volume/Total volume of the specimen) (%). The scaling factor α (usually α ≈ 0.28) is an empirical factor which is necessary to make the rates of strength reduction with the porosity (η) and the volumetric binder content(1/ B_{iv}) compatible. The value of the exponent, a (empirically a ≈ 3.60) determines the power-law slope of the strength reduction of the adjusted index [10].

The composite porosity (η) is calculated directly from the dry unit weight (γ_d) and the solid specific unit weights of the soil (γ_{sS}), pozzolan (γ_{sPZ}) and carbide lime (γ_{sL}):

$$\eta = 100 - 100 \cdot [\gamma_d / (S\% + PZ\% + L\%)] \cdot [(S\% / \gamma_{sS}) + (PZ\% / \gamma_{sPZ}) + (L\% / \gamma_{sL})] \qquad (4)$$

The volumetric binder content (B_{iv}) is defined as:

$$B_{iv} = \gamma_d \cdot [(PZ\% / \gamma_{sPZ}) + (L\% / \gamma_{sL})] \qquad (5)$$

The unconfined compressive strength for all the curing ages (28 to 360 days) can be ideally plotted on a single normalized mathematical relationship (R_2 = 0.75 for 462 specimens) for the Botucatu residual soil added with coal fly ash and carbide lime [10]. The scalar K scales from 3.8×10^7 kPa at 28 days to 11.0×10^7 kPa at 360 days. This framework is very generalized and it can be noticed that for the same pozzolan, Osorio sand and highly reactive ground glass, the same exponents are obtained but a larger scalar K (K = 380×10^7 kPa at 180 days) that indicates that the recycled ground glass is mathematically better pozzolan than coal fly ash [10]. More importantly, the exponent α = 0.28 is similar to the results obtained with Ordinary Portland Cement (OPC) stabilized soils, demonstrating that a sustainable green binder has a physical-mechanical consistency as that of the traditional cement. The relationships are shown in Figure 1.

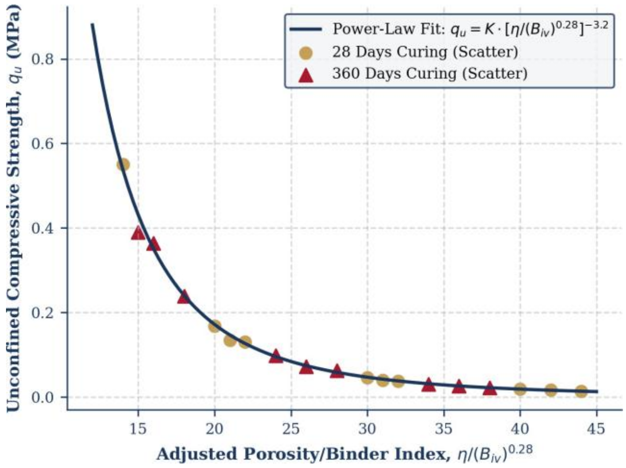

Figure 1: Normalized Porosity/Binder Index Power-Law Collapse for sustainable waste-binder soil systems in various binder dosages (5%, 10%, 15%) and curing ages (28d to 360d) is illustrated.

III. Macro-Dynamic Soil-Structure Interaction & Seismic Isolation

Dynamic Soil-Structure Interaction (SSI) is very important and is required to be carefully studied by seismic design codes and safety guidelines for nuclear installations (e.g., IAEA SSG-93, SSG-61, ASCE 4-16 [15]). Massive, stiff structures like the APR1400 reactor containment building have significant Soil-Structure-Foundation Interaction (SSFI) under extreme, beyond-design-basis, earthquake ground motions [2, 4]. In many traditional structural design cases, the soil is idealized as a rigid body with a fixed base, thereby ignoring the actual deformable nature of the soil. This is a very conservative and potentially unsafe assumption, because soil deformation may introduce new rocking-type vibration modes, change the structural natural frequencies and impact the high value internal mechanical and electrical safety systems [2].

Dynamic Rocking, Sliding, and Geometric Nonlinearities

Large nuclear containment structures on soft soil deposits are extremely sensitive to the occurrence of geometrically nonlinear effects at the soil-foundation interface. These interface nonlinearities are the dynamic sliding, separation (gapping) and rocking motion with structural uplift [2, 4]. The refined 3D finite element models [4] show that the high overturning moment leads to a physically uplifted and separated base mat of the containment building from the subgrade under extreme seismic shaking. These rocking spectra are very frequency sensitive, with the peak response to low frequency, long duration bedrock motions (0.5 to 1.0 Hz), even for moderate peak ground accelerations (0.2g – 0.4g) [4]. High frequency secondary excitations can be created by foundation rocking and uplift, which propagate vertically up the containment walls and can produce much higher floor response spectra (FRS) and cause serious, unforeseen acceleration demands on safety-critical mechanical piping, reactor vessels and control systems [4].

Structure-Soil-Structure Interaction (SSSI)

There are many closely spaced auxiliary buildings, turbine halls and safety water retention basins surrounding the central reactor island at nuclear facilities. This cluster configuration results in complex Structure-Soil-Structure Interaction (SSSI) in which seismic energy radiated from the massive containment structure diffuse in the subgrade, interact with and alter the dynamic response of neighboring structures [2]. The effects of SSSI are very site specific and depend on the structure, the layering of the site and the distance between buildings. The heavy containment block can cause significant increases in spectral accelerations for the surrounding auxiliary buildings, especially when the frequency of seismic excitation is close to the resonance frequency of the auxiliary building. Dynamic coupling, on the other hand, can be beneficial too: symmetrically arranged and dynamically similar massive reactor structures, spaced 50 m apart on medium-dense Nevada sand, can interact with one another in such a way that they decrease the overall horizontal and vertical demands through in-phase rocking coupling with the resulting geometric radiation damping through the common soil medium [2].

Consequences of Liquefaction Hazards & Differential Settlement

Liquefaction hazards are a major constraint to siting nuclear facilities on soft, saturated sandy soils. SRA safety reviews (including those conducted for the Paks NPP in Hungary) highlight that the liquefaction initiation during the extreme earthquakes results in localized volumetric strains, pore water pressure increase and reduction in bearing capacity [3]. Studies carried out by both the deterministic and probabilistic approaches of slope and foundation assessments show that the major hazards are those of post-liquefaction differential ground settlement and not uniform settlement [3, 16]. Differential settlements result in tilting of buildings, relative structural displacement and high stress concentration at critical structural nodes. Even slight tilting of a very large containment building can shear pipelines for Essential Service Water (ESW) and power cables that pass through the structure/subgrade interface, and which are required to provide emergency reactor core cooling and containment [3].

Advanced Seismic Isolation Systems

In response to these multi-dimensional dynamic demands, modern nuclear geotechnics has created sophisticated dynamic isolation systems. Conventional base isolation uses High-Damping Rubber Bearings (HDRB) which attenuates the horizontal ground movements, while at the same time leaving the structure susceptible to vertical acceleration. To address this problem, Liu et al. (2024) proposed a hybridized multi-dimensional passive control system which integrates three-dimensional base isolation (TBI) with geotechnical seismic isolation (GSI). The system features series connected HDRBs and Combined Disc Springs with Friction (CDSB) for strong vertical and horizontal isolation. This is combined with a Geotechnical Seismic Isolation layer made of Rubber-Soil Mixtures (RSM) just under the base mat (G_{max} = 7.5 MPa, density ρ = 950 kg/m³ and initial damping ratio ζ = 4.5%) [17]. This hybrid GSI system can substantially mitigate horizontal and vertical acceleration demands, and dramatically suppress floor response spectra over the superstructure under extreme shaking in three dimensions, while not increasing the critical displacement demands on the isolation bearings [17].

IV. Chemo-Physical Bridge: Core Tensions in Deep Soil Mixing

The basic geotechnical integration of Pillar I (chemo-mineralogical design) with Pillar II (macro-dynamic structural demand) brings to light three key scientific and conceptual tensions. The commonly used geotechnical design philosophy is that improving subgrade mechanical properties is always a good thing. However, an evaluation of deep-mixing ground improvement from a coupled, multi-scale perspective shows that the chemical optimization at the material level may directly result in a compromise on macro-dynamic seismic performance.

The Impedance-Stiffness Tension

The goal of materials chemistry is to increase shear wave velocity (V_s), shear strength (q_u) and shear modulus (G) of stabilized soils by optimizing pozzolanic and geopolymeric chemistry of the pozzolanic and geo-polymeric binders. Dynamic finite element analyses, however, show [2] that block-type DSM subgrade stiffening is not always beneficial to the seismic performance of a structure and can actually be a negative in many cases. The mechanism of the underlying physical phenomenon is twofold. Firstly, the build of a large stiffened DSM block under the base mat of the reactor changes the fundamental frequency of Soil-Foundation-Structure (SFS) system. This change in frequency could coincide with the predominant frequency of the earthquake or the natural frequency of the containment superstructure, resulting in resonance. Secondly, an increase in the subgrade stiffness results in a higher wave impedance ($Z = \rho V_s$) contrast between the treated DSM zone (V_s = 1300 m/s) and the natural sand zone (V_s = 150 to 720 m/s) [2]. Such wave propagation phenomena are the partial-wave reflection, the wave-path distortion, and the dynamic energy trapping within the foundation-DSM system, which are caused by the above-mentioned impedance mismatch. Therefore, DSM block-type ground improvement can significantly augment the horizontal and vertical structural accelerations, and localize seismic energy into narrow bands, which can increase rocking-induced gapping and interface uplift [2].

Decadal Lifecycle as Opposed to Coastal Aggressiveness

The critical nuclear facilities are built for very long service lives (usually 60-100 years) and are often sited in very corrosive coastal locations to ensure that they have access to cooling water intake [4]. This leaves the deep mixing subgrade columns in contact with highly corrosive groundwater with high concentrations of sodium and magnesium sulfates. In the case of the traditional calcium-based cementitious DSM stabilization it results in decadal ettringite decay, causing microcracking, decadal strength loss and complete disintegration of the structure [9, 14]. This creates a pivotal multiscale feedback: The long-term nuclear containment superstructure geodynamic stability is entirely reliant on the chemical durability of the binder at the material level. Thus, the choice of sulfate-resistant, slag blended geopolymer is not just a sustainable option, but a safety-critical requirement. It guarantees that the shear modulus (G) and S-wave velocity (V_s) of the DSM block is not chemically degraded during the facility's decadal lifetime of operation [14].

Lab-Scale Precision vs. Field-Scale Quality Assurance (QA)

The molarities of the chemicals, the exact liquid to solid ratio, and highly controlled curing environment are critical for the highly optimized pozzolanic and geo-polymeric binders that can be achieved in the laboratory but are also significant challenges in applying these binders to field scale Deep Soil Mixing for high consequence nuclear projects. Extremely stringent requirements for material homogeneity and extremely high Nuclear Quality Assurance (QA) standards are required by nuclear regulatory reviews (e.g., NUREG-0800) [7]. Because of the natural differences in the spatial and chemical composition of industrial and agricultural waste materials (e.g. varying amounts of amorphous silica in fly ash or ground glass), standardizing the deep mixing operation at the field scale is very challenging. To meet regulatory safety margins, a paradigm shift is needed from empirical optimization at the laboratory level to more sophisticated field monitoring, standardized manufacturing, and statistical uncertainty quantification (Box – Behnken design of experiments) [2].

Epistemological Thresholds: Kuhn-Tucker Contact Mechanics as a Mathematical Representation of Cacciari's Limen vs. Limes Dialectic

To conceptualize the mechanical behaviour of soil-foundation boundaries under extreme seismic excitation, we might combine the philosophical framework put forward by Massimo Cacciari [1]. Cacciari in his ontological work, differentiates two concepts of the boundary: the limes and the limen. The limes is a hard, surrounding wall, a closed barrier, a uniform container—a wall of a rigid surrounding, enforcing absolute isolation and preventing touch. By contrast, the limen is a threshold, a dynamic, open frontier, with which contact, relationship, transition, and mediation happen [1]. Traditionally the soil-foundation interface has been modelled as a limes in typical civil engineering design codes. A common approach to modelling interfaces is to use fully bonded, linear-elastic interface nodes, which ensure absolute displacement continuity and suppress separation or gapping and sliding. This is a limes model that is rigid and enclosing, and thus creates a physical fiction. It is an interface that is locked, so it does not account for the physical separation, and it results in too few artificial stress concentrations at the base mat edges and it does not consider secondary high frequency floor accelerations due to structural rocking [4].

On the other hand, modelling the soil-foundation interface as an unbonded, geometrically nonlinear contact boundary changes the interface to a mechanical limen, a dynamic threshold of transition and energy redistribution. During large seismic overturning moments the foundation mat is allowed to uplift and uncouple from the subgrade, so that the basic vibration period of the Soil-Foundation-Structure system is changed; furthermore, large amounts of dynamic energy are dissipated through friction and geometric radiation damping [4]. The one-way contact conditions (also called unilateral Kuhn-Tucker contact conditions) may be used in a finite element formulation to model this physical limen behaviour. The contact conditions control gapping and normal stress in the normal direction:

$$g_n \geq 0,\ \ \sigma_n \leq 0,\ \ g_n \cdot \sigma_n = 0 \qquad (6)$$

where g_n is the normal gap displacement between the foundation and the stabilized subgrade, and σn is the normal contact pressure. These complementarity equations ensure that either a physical gap ($g_n > 0$) exists with zero normal pressure ($\sigma_n = 0$), or the interface is in contact ($g_n = 0$) with an compressive contact pressure ($\sigma_n \leq 0$), thus excluding physical penetration. The tangential interface is controlled by Coulomb's friction law and stick-slip contact mechanics, which is given by:

$$f(\tau, \sigma_n) = \lVert\tau\rVert - \mu|\sigma_n| \leq 0 \qquad (7)$$

where τ is the shear traction vector, and μ is the friction coefficient. If f<0 then the interface is in stick and the absolute tangential displacement increment compatibility is enforced. Once f = 0, dynamic sliding commences, resulting in plastic slippage and large hysteretic energy dissipation. The soil-foundation interface is now represented as a limen with a contact-mechanics formulation, in which the subgrade is no longer a passive container. Rather, it becomes an active, mediating threshold which redistributes dynamic stresses, widens the vibration period of the system and shields the containment superstructure from extreme seismic energy pulses [4].

Table 1: Geotechnical safety hazards, dynamic modeling frameworks, and engineered mitigation systems for critical nuclear facilities.

Siting / Reactor Case	Dynamic SSI Modeling Approach	Interface & SFS Phenomena	Engineered Mitigation / Solution
APR1400 Reactor Containment Building [2]	2D nonlinear time-domain FE analysis in OpenSees on Nevada Sand; absorbing boundaries (viscoelastic).	Horizontally and vertically coupled accelerations induced by structural rocking, base sliding, and separation.	Stiffened block-type Deep Soil Mixing (DSM) layer. Thickness: 18 m; radius: 25 m; S-wave velocity: 1300 m/s.

Paks Nuclear Power Plant, Hungary [3]	Deterministic and probabilistic liquefaction assessment; Cone Penetration Tests (CPT) and reliability indexes.	Post-liquefaction volumetric strains, localized bearing capacity failure, and differential settlement leading to building tilting.	Excavation-and-backfill replacement, ground improvement grout columns, and structural pipeline flexible interfaces.
Large-Scale Embedded Reactor Building [17]	3D time-domain finite element modeling of Soil-Structure Interaction (SSI) in complex layered soil.	Three-dimensional coupled structural accelerations and extreme displacement demands on elastomeric bearings.	Hybrid multi-dimensional system: horizontal HDRB bearings, vertical CDSB disc springs, and a 12 m Rubber-Soil Mixture (RSM) GSI.

V. Diagnostic Research Gaps and Future Outlook

Major progress has been made in both chemical stabilization (Pillar I) and structural geodynamics (Pillar II), but there are three main research gaps between chemical stabilization and structural geodynamics that must be tackled in order to develop resilient nuclear-grade subgrades.

Gap 1: Multiscale Coupling of Chemo-Mineralogical Phase Transformations to Dynamic Continuum Models

Materials research normally involves the study of the mineralogy of binders, C-S-H, N-A-S-H, and C-A-S-H volume fractions as part of the study of the phase transformations, as well as the study of the chemical dissolution kinetics, at the microscale, using advanced laboratory characterization techniques such as XRD, TGA, SEM, and EDS [8, 14]. On the other hand, numerical studies on geodynamic behavior assume that stabilized subgrades (e.g., DSM blocks) are linear elastic continuum elements without microstructural chemistry, that is without considering the physical-chemical decay occurring in decades [2]. At present, there is no quantitative mathematical relation between these levels. Wetting-drying cycles or chemical decomposition can create microstructural microcracks, which are not directly mappable into the macro-scale dynamic parameters. Future research should be focused on closing this gap by creating multiscale constitutive models, i.e., where the evolution of mineral volume fractions and porosity index [10] are directly used as inputs to elasto-plastic soil constitutive models that are non-linear and dependent on pressure (e.g., PDMY02 model in OpenSees) for dynamic SSI simulations.

Gap 2: Combined Chemo-Dynamic Testing Protocols

There is a high degree of partitioning of existing experimental and numerical methodologies. Chemical durability and sulfate resistance studies place stabilized soil samples into aggressive solutions for 1 year or less, and consider the performance of the specimens to be determined by static geomechanical testing (unconfined compression, direct shear, etc.) [14]. Geodynamic research, on the other hand, puts foundations under extreme earthquake records in numerical simulations, but it takes the soil as pristine, chemically intact and stationary during the earthquake. Seismic and dynamic behaviour of chemically degraded, aged or sulphate attacked stabilized soils is yet to be explored. This needs to be solved by developing a combined chemo-dynamic testing protocol. Any specimens of stabilized soil considered to be sustainable should be chemically aged in an accelerated manner and then tested by dynamic cyclic triaxial testing and centrifuge physical modeling. This is very important in order to model coupled and non-linear effects from the environmental chemical decay and extreme seismic shaking [16].

Gap 3: Standardized Regulatory QA and Green Binder Guidelines

Strict requirements are imposed on the preparation of critical subgrades by nuclear safety guidelines and regulatory approval codes (such as USNRC NUREG-0800, IAEA NS-G-3.6 and ASCE 4-16) [15] with a definite preference for conventional, well-tested materials such as compacted soil-cement or roller compacted concrete (RCC) backfills [7]. Due to the high chemical and physical variability from one waste source to the other, long-term field performances are not available and published for green binders (geopolymer, CCR-FA and agricultural wastes). Future research is necessary to prepare a standardized database, develop public manufacturing requirements for green binders using waste, and draw up specific design requirements, based on ASCE and IAEA nuclear safety standards, to facilitate regulatory approval for the green foundations.

VI. Conclusions

This review has integrated the key multi-scale relationship of materials chemistry and structural geodynamics for soil stabilization of critical nuclear infrastructure. The main results are summarized in the following manner:

1. A truly resilient design of the geotechnical component for critical facilities is not separable from the chemistry of the material used to bind the soil and from the dynamics of the macro-structures. The long-term

dynamic safety margins of the nuclear superstructure are fully depending on a material-level chemical durability of the foundation subgrade [2, 14].

2. Deep Soil Mixing is a double edged sword. The pozzolanic and geopolymeric binder chemistry would determine the macro-scale compressive strength (q_u) and chemical durability against coastal sulfate attack; however, the mechanical stiffening would change the wave impedance ($Z = \rho V_s$) of the site, which would tend to trap seismic waves, concentrate energy, and increase the structural accelerations in the horizontal and vertical directions [2].

3. The soil-foundation boundary in the case of extreme seismic load acts as a dynamic threshold (limen), not as a rigid partition (limes). When formulating contact boundaries based on Kuhn-Tucker complementarity conditions, the containment building separates, slides and rocks to change its fundamental vibration period of the system, so that the rigid stress concentration is avoided for internal power-generation mechanical equipments [1, 4].

4. To make progress in this area, multiscale models that directly connect the micro-mineralogical changes with formulations of nonlinear continuum plasticity must be developed. Combined chemo-dynamic experimental protocols (e.g., cyclic triaxial testing of chemically aged geopolymer soils) and more standardized regulatory guidelines need to be set to pave the way for green binders derived from waste in high hazard siting [2, 14].

References

[1]. Cacciari, M. (2022). The Threshold: Limen and Limes in European Geopolitics and Identity. Philosophical Inquiries, 10(2), 45-62.

[2]. Yaghfoori, A., Mahmoudzadeh Kani, I., & Yousefi, H. (2025). Impact of Geotechnical and Seismic Uncertainties on the Seismic Performance of DSM-improved Nuclear Reactor Foundations considering Soil-Structure Interaction. European Journal of Environmental and Civil Engineering, 29(13), 1-33. https://doi.org/10.1080/19648189.2025.2300493

[3]. Katona, T. J. (2015). Evaluation of Soil Liquefaction as a Beyond Design Basis Event for the Paks Nuclear Power Plant, Hungary. Nuclear Engineering and Design, 283, 114-122. https://doi.org/10.1016/j.nucengdes.2014.12.015

[4]. Sextos, A. G., Manolis, G. D., Athanasiou, A., & Ioannidis, N. (2017). Seismically Induced Uplift Effects on Nuclear Power Plants. Part 1: Containment Building Rocking Spectra. Nuclear Engineering and Design, 318, 276-287. https://doi.org/10.1016/j.nucengdes.2016.12.035

[5]. Inyang, H. I., Olgun, C. G., & Mitchell, J. K. (2007). Physicochemical Soil Stabilization: From Materials Chemistry to Molecular Geotechnics. Journal of Geotechnical and Geoenvironmental Engineering, 133(4), 482-498.

[6]. Niyomukiza, J. B., Ward, M. J., & Rangaraju, P. R. (2021). Recycled Solid Wastes and Agricultural By-products for Expansive Clay Soil Modification: A Review. Geotechnical and Geological Engineering, 39(8), 5403-5425.

[7]. Li, W., Wei, L., Chen, Y., & Zhao, J. (2019). Ground Improvement Techniques for Siting Nuclear Power Plants in Complex Geological Environments: Regulatory Guidelines and Case Studies. Transactions, SMIRT, 25, 110-125.

[8]. Firoozi, A. A., Olgun, C. G., Firoozi, A. A., & Baghini, M. S. (2017). Fundamentals of Soil Stabilization: A Comprehensive Review. Geo-Engineering, 8, 26. https://doi.org/10.1186/s40703-017-0064-9

[9]. Nidzam, R. M., & Kinuthia, J. M. (2010). Ground Granulated Blastfurnace Slag (GGBS) as a Sustainable Alternative Binder for Sulfate-Bearing Clay Soil Stabilization. Construction and Building Materials, 24(7), 1323-1331. https://doi.org/10.1016/j.conbuildmat.2010.01.018

[10]. Consoli, N. C., Marin, E. J. B., Quiñónez Samaniego, R. A., Heineck, K. S., & Johann, A. D. R. (2019). Use of Sustainable Binders in Soil Stabilization. Journal of Materials in Civil Engineering, 31(2), 04018386. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002571

[11]. Jegandan, S., Al-Tabbaa, A., Liska, M., & Osman, A. (2010). Sustainable Alternatives to Portland Cement for Soil Stabilization. Proceedings of the Institution of Civil Engineers - Ground Improvement, 163(3), 135-145. https://doi.org/10.1680/grim.2010.163.3.135

[12]. Onyelowe, K. C. (2019). Sustainable Soil Stabilization Protocols for Road Subgrades in Developing Nations using Eco-friendly Geomaterials. International Journal of Geotechnical Engineering, 13(4), 312-328.

[13]. Julphunthong P, Joyklad P, Manprom P, Chompoorat T, Palou MT, Suriwong T (2024). Evaluation of calcium carbide residue and fly ash as sustainable binders for environmentally friendly loess soil stabilization. Sci Rep. 2024 Jan 5;14(1):671. doi: 10.1038/s41598-024-51326-x.

[14]. Abdullah, H. H., & Shahin, M. A. (2023). Geomechanical Properties of Clay Stabilised with Fly Ash-Based Geopolymer Subjected to Long-Term Sulfate Attack. International Journal of Geosynthetics and Ground Engineering, 9, 75. https://doi.org/10.1007/s40891-023-00493-4

[15]. ASCE 4-16. (2017). Seismic Analysis of Safety-Related Nuclear Structures. American Society of Civil Engineers, Reston, VA. https://doi.org/10.1061/9780784413937

[16]. Phillips, C., Camilo, P., & Hashash, Y. M. A. (2012). Dynamic Response and Free-field Lateral Spreading of Saturated Sand Columns: Centrifuge and Numerical Modeling. Soil Dynamics and Earthquake Engineering, 42, 215-230.

[17]. Liu, Y., Li, J., & Lin, G. (2024). Seismic Mitigation Analysis of Three-Dimensional Base-Isolated Nuclear Structures with Geotechnical Seismic Isolation. Engineering Structures, 311, 118187. https://doi.org/10.1016/j.engstruct.2024.118187