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

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Abstract: *Geotechnical subgrade preparation for high-consequence structures, such as nuclear power plants (NPPs) and Small Modular Reactors (SMRs), represents one of the most demanding disciplines in civil engineering due to the extreme structural loads and safety margins involved. This state-of-the-art review paper bridges two traditionally distinct domains: micro-scale material chemistry of sustainable soil stabilizers (Pillar I) and macro-scale structural Soil-Structure-Foundation Interaction (SSFI) under dynamic seismic excitation (Pillar II). Deep Soil Mixing (DSM) is evaluated as the critical, multiscale physical-chemical interface connecting these disciplines. At the material level, we analyze the pozzolanic and geopolymeric gelation kinetics (forming calcium-silicate-hydrate and sodium/calcium-aluminate-silicate-hydrate frameworks) of eco-friendly binders derived from industrial and agricultural waste materials (e.g., coal fly ash, calcium carbide residue, ground granulated blast-furnace slag). We address the suppression of sulfate-induced ettringite heave, a key vulnerability of conventional cement, and review the mathematical normalization of geomechanical properties via Consoli's porosity/binder index. At the structural level, we analyze geometrically nonlinear SSFI phenomena (including sliding, separation/gapping, and rocking-induced uplift) and Structure-Soil-Structure Interaction (SSSI) in clustered nuclear islands. Crucially, we highlight a fundamental chemo-physical tension: chemical optimization to maximize binder compressive strength elevates subgrade shear wave velocity, producing dynamic wave impedance contrasts that trap seismic energy and amplify horizontal and vertical structural accelerations. Finally, we reframe this contact boundary through Massimo Cacciari's philosophical dialectic of the open threshold (limen) versus the rigid boundary (limes), demonstrating that modeling the interface as an unbonded contact boundary under Kuhn-Tucker unilateral constraints is a physical necessity to capture the floor response spectra that govern critical internal equipment. Primary research gaps and a roadmap for unified chemo-dynamic modeling are presented.*

Key Words: *Sustainable Soil Stabilization; Deep Soil Mixing; Soil-Structure-Foundation Interaction; Alkali-Activated Geopolymers; Nuclear Geotechnical Safety.*

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I. Introduction

Geotechnical site evaluation and subgrade engineering are foundational pillars of nuclear safety, directly dictating the structural integrity of Nuclear Power Plants (NPPs) and Small Modular Reactors (SMRs) under both static and extreme dynamic loading conditions. Unlike typical civil infrastructure, nuclear installations feature exceptionally high dead weights, deep structural embedment, and rigorous seismic safety margins designed to prevent catastrophic beyond-design-basis accidents [1, 2]. Problematic subgrade conditions—such as highly plastic clays, loose saturated sands, or chemically unstable coastal deposits—introduce complex geotechnical risks. 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 requires a holistic geotechnical strategy that transitions beyond empirical index testing into rigorous, multiscale physical and chemical analysis.

In modern nuclear geotechnics, soil stabilization has evolved from traditional, trial-and-error physical modification (such as compaction or mechanical blending) to advanced physicochemical subgrade engineering rooted in materials chemistry, chemical mineralogy, and thermodynamic equilibrium [5, 6]. Ground improvement protocols must satisfy strict regulatory codes (e.g., IAEA SSG-93, SSG-61, and USNRC NUREG-0800 Section 2.5.4) that mandate comprehensive site characterization, continuous field monitoring, and rigorous quality assurance schemes [7]. The primary structural engineering vehicle for executing this stabilization is

block-type Deep Soil Mixing (DSM) and compact engineered backfills, which chemically bind weak natural ground into a high-performance, monolithic foundation support [2, 7].

This state-of-the-art review paper bridges two traditionally isolated disciplines within geotechnical engineering: the micro-scale materials chemistry of sustainable pozzolanic and geopolymeric 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). By synthesizing these domains, we address the fundamental chemo-physical tensions inherent to DSM. We analyze how optimizing chemical binders for compressive strength can counterproductively alter the wave impedance of the site, introducing localized energy focusing, resonant amplification of horizontal and vertical spectral accelerations, and foundation rocking with geometric gapping and uplift [2, 4]. Finally, we translate this mechanical separation into a formal mathematical contact representation based on Massimo Cacciari's [1] philosophical dialectic of the threshold (limen) versus the boundary (limes), providing a novel paradigm for critical facility design.

II. Advances in Chemo-Mineralogical Soil Stabilization

The chemical modification of clayey and expansive soils is traditionally dominated by high-calcium additives such as Ordinary Portland Cement (OPC) and hydrated lime. While highly effective in ambient conditions, these conventional stabilizers suffer from severe environmental and technical vulnerabilities. OPC manufacturing alone accounts for approximately 8% to 10% of global CO2 emissions due to the decarbonization of limestone and fossil-fuel intensive burning [8]. Mechanically, cement-treated soils exhibit highly brittle failure modes and a high tendency for microcracking. Most critically, in sulfate-bearing clays—frequently encountered in coastal areas targeted for nuclear cooling water intake—the calcium-based hydrated phases trigger a catastrophic swelling and heave phenomenon known as ettringite and thaumasite distress [8, 9].

Chemistry of Sulfate-Induced Heave (Ettringite Distress)

When calcium-based stabilizers (lime or OPC) are mixed with sulfate-bearing clays, the high alkalinity (pH > 12) dissolves the clay minerals, releasing highly reactive amorphous alumina and silica. In the presence of soluble sulfate ions (from groundwater or soil) and calcium, these dissolved species react to precipitate the highly expansive, needle-like mineral ettringite [hydrous calcium aluminum sulfate: Ca6Al2(SO4)3(OH)12·26H2O] [8, 9]. The chemical reaction is formulated as:

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

Upon contact with water, ettringite crystals undergo extreme hydration-induced swelling, generating crystallization pressures exceeding 2 to 3 MPa. This pressure vastly surpasses the tensile strength of the stabilized soil, leading to microstructural disintegration, severe macro-heaving, and the complete loss of bearing capacity [8, 9]. Under lower temperature conditions (typically < 15 °C) and in the presence of carbonate sources, ettringite can undergo mineralogical transformation to thaumasite [Ca3Si(OH)6(CO3)(SO4)·12H2O], which directly attacks the calcium-silicate-hydrate (C-S-H) binder gel, converting the stabilized soil into a cohesionless mush [8].

Alternative and Sustainable Green Binders

To mitigate sulfate heave while minimizing the carbon footprint of geotechnical operations, recent materials research has prioritized cement-free, sustainable binders synthesized from industrial, agricultural, and domestic by-products. This circular economy approach focuses on coal fly ash (Class C and Class F), 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 function as highly reactive pozzolans, supplying the necessary silica and alumina. CCR, a hazardous domestic byproduct of acetylene gas production, acts as a portlandite-rich [Ca(OH)2] activator [6, 10]. Pozzolanic reactions proceed as the dissolved portlandite combines with amorphous silica and alumina, precipitating stable Calcium-Silicate-Hydrate (C-S-H) and Calcium-Aluminate-Hydrate (C-A-H) gels that encapsulate soil particles [10]. The optimal chemical balance is achieved at a Ca/(SiO2 + Al2O3) ratio of 1.5, which maximizes unconfined compressive strength (UCS) and durability against wet-dry cycling, although microcracking can manifest after extended exposure [13].

Alkali-Activated Geopolymerization and Ettringite Suppression

Alkali-activated geopolymerization represents the state-of-the-art in sustainable ground stabilization. Geopolymers are synthesized by activating low-calcium, high-aluminosilicate materials (such as fly ash or metakaolin) with a highly concentrated alkaline solution (commonly sodium silicate [Na2SiO3] and sodium hydroxide [NaOH]) [14]. This chemical process proceeds through four distinct kinetic stages: (1) complete dissolution of aluminosilicate minerals by highly concentrated hydroxyl ions (OH−); (2) diffusion and

reorganization of the dissolved silicate and aluminate monomers; (3) chemical polycondensation between alkali metal cations (Na+ or K+) and the monomers, precipitating an amorphous, three-dimensional Sodium Aluminate Silicate Hydrate (N-A-S-H) gel framework; and (4) gel hardening that binds soil aggregates mechanically [14]. To accelerate ambient-temperature curing, GGBS is blended to precipitate coexisting, calcium-aluminate-silicate-hydrate (C-A-S-H) gel networks, which rapidly enhance mechanical strength [14].

Crucially, geopolymers suppress ettringite formation. Replacing 60% to 80% of lime or OPC with GGBS consumes available calcium in stable, non-expansive C-A-S-H gels and restricts alumina mobility [9]. Under long-term (1-year) immersion in high-concentration (50 g/L) sodium sulfate (Na2SO4) and magnesium sulfate (MgSO4) solutions, geopolymer-treated clay maintains outstanding geomechanical and volumetric stability, with maximum volumetric changes remaining below 1.2%, far below the typical 10% structural failure threshold [14]. But magnesium sulfate represents a significantly more aggressive chemical environment than sodium sulfate. The magnesium ion (Mg2+) undergoes hydrolysis, releasing hydrogen ions that gradually acidify the pore solution [14]:

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

This acidification buffers the high alkalinity of the geopolymer matrix, reducing the residual pH from its optimal level (> 12) down to 10.1 in magnesium sulfate, compared to 10.6 in sodium sulfate and 11.2 in tap water [14]. Because geopolymerization requires a pH ≥ 12 to maintain continuous dissolution and polycondensation, this localized pH reduction slows down the reaction kinetic gain, resulting in lower peak unconfined compressive strength (qu) and lower stiffness modulus (E50) over decadal lifecycles [14].

Geomechanical Normalization: Consoli's Porosity/Binder Index

To establish a rational, scientific dosage methodology for sustainable waste-binder blends, Consoli et al. [10] proposed a mathematical normalization framework based on the porosity/binder index. This rational model demonstrates that the unconfined compressive strength (qu) of stabilized soils is controlled by a single, governing physical index, formulated as:

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

where K is a scalar parameter (in kPa) that is unique to each specific soil-binder system and increases with curing time to reflect the progress of chemical cementation [10]. The index η represents the porosity of the compacted blend (%), while Biv is the volumetric content of the binder (defined as pozzolan plus carbide lime or geopolymer), expressed as a percentage of binder volume to the total volume of the specimen. The exponent α (typically α ≈ 0.28) is an empirical scaling factor required to make the rates of strength variation with porosity (η) and the volumetric binder content (1/Biv) compatible. The exponent a (empirically a ≈ 3.60) controls the power-law slope of the strength reduction with the adjusted index [10].

The composite porosity (η) is calculated directly from the dry unit weight (γd), and the solid specific unit weights of the soil (γsS), pozzolan (γsPZ), and carbide lime (γsL):

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

The volumetric binder content (Biv) is defined as:

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

For Botucatu residual soil mixed with coal fly ash and carbide lime, the unconfined compressive strength across all curing ages (from 28 to 360 days) perfectly collapses onto a single, normalized mathematical relationship ($R^2 = 0.75$ for 462 specimens) [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 highly generalized, holding true for Osorio sand mixed with highly reactive ground glass and carbide lime, yielding identical exponents but a larger scalar K ($K = 380 \times 10^7$ kPa at 180 days), demonstrating that recycled ground glass is a mathematically superior pozzolan compared to coal fly ash [10]. Crucially, the exponent $\alpha = 0.28$ matches that of soils stabilized with Ordinary Portland Cement, proving that sustainable green binders exhibit a physical-mechanical consistency identical to traditional cement. Figure 1 presents the relationships.

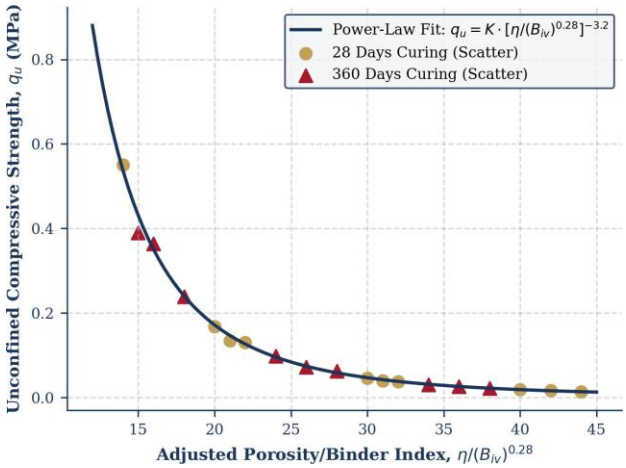

Figure 1: Normalized Porosity/Binder Index Power-Law Collapse across variable binder dosages (5%, 10%, 15%) and curing ages (28d to 360d) for sustainable waste-binder soil systems.

Table 1: State-of-the-art chemo-mineralogical binder systems, gel hydration mechanisms, and predictive index models.

Stabilizer / Binder System	Hydration / Main Geopolymeric Gel Phases	Long-term Durability Performance	Mechanical Prediction Index (Consoli model)
Calcium Carbide Residue (CCR) & Fly Ash (FA) [10]	C-S-H (Calcium Silicate Hydrate) and C-A-H (Calcium Aluminate Hydrate) crystalline gels.	Vulnerable to microcracking after 12 wet-dry cycles due to loess volume expansion.	qu = K · [η/(Biv)^0.28]^(−3.60) where K scales up to 11.0 × 10^7 kPa at 360 days.
Alkali-Activated Fly Ash-Slag Geopolymer [14]	Coexisting amorphous N-A-S-H (Sodium Aluminate Silicate Hydrate) and C-A-S-H networks.	Highly durable under 1-year coastal sulfate attack; maximum volume change < 1.2% (no ettringite).	qu peak increases with curing age; strength gain hindered in MgSO4 due to pH buffering.
Ground Waste Glass & Carbide Lime [10]	Highly reactive C-S-H gel networks driven by fine amorphous silica content in waste	Superb decadal stability; glass acts as a highly efficient pozzolan; superior to coal fly ash.	qu = K · [η/(Biv)^0.28]^(−3.60), with K = 380 × 10^7 kPa at 180 days (highly active).

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

Seismic design codes and safety guidelines for nuclear installations (such as IAEA SSG-93, SSG-61, and ASCE 4-16 [15]) mandate the rigorous evaluation of dynamic Soil-Structure Interaction (SSI). Under extreme, beyond-design-basis earthquakes, massive and stiff structures—such as the APR1400 reactor containment building—experience substantial Soil-Structure-Foundation Interaction (SSFI) [2, 4]. Traditional structural design frequently assumes a rigid, fixed-base condition, which completely overlooks the real-world deformable behavior of the soil. This assumption is highly conservative and potentially dangerous, as soil deformation can introduce additional rocking-type vibration modes, alter the structural natural frequencies, and modify the demand on high-value internal mechanical and electrical safety systems [2].

Dynamic Rocking, Sliding, and Geometric Nonlinearities

Heavy nuclear containment buildings founded on soft soil deposits are highly susceptible to geometrically nonlinear phenomena at the soil-foundation interface. These interface nonlinearities include dynamic sliding, separation (gapping), and rocking motion with structural uplift [2, 4]. Refined 3D finite element models [e.g., 4] demonstrate that during extreme seismic shaking, the high overturning moment causes the base mat of the containment building to physically separate and uplift from the underlying subgrade. These rocking spectra are highly frequency-sensitive, peaking in response to low-frequency, long-duration bedrock motions (typically in the 0.5 to 1.0 Hz range), even at moderate peak ground accelerations (0.2g to 0.4g) [4]. Foundation rocking and uplift can generate high-frequency secondary excitations that propagate vertically up the containment walls, significantly amplifying the floor response spectra (FRS) and subjecting safety-critical mechanical piping, reactor vessels, and control systems to severe, unexpected acceleration demands [4].

Structure-Soil-Structure Interaction (SSSI)

Nuclear facilities typically feature closely spaced auxiliary buildings, turbine halls, and safety water retention basins arranged around the central reactor island. This cluster layout gives rise to complex Structure-Soil-Structure Interaction (SSSI), where seismic energy radiated from the massive containment structure propagates through the subgrade, coupling with and modifying the dynamic response of adjacent structures [2]. SSSI effects are highly case-specific and dependent on structural characteristics, site layering, and the spacing

between buildings. The presence of a heavy containment block can dramatically increase the spectral accelerations of neighboring auxiliary buildings, particularly when the seismic excitation frequency matches the auxiliary building's resonance frequency. Conversely, dynamic coupling can also be beneficial: symmetrically arranged, dynamically similar massive reactor structures (spaced 50 m apart on medium-dense Nevada sand) can mutually interact to reduce overall horizontal and vertical demands via in-phase rocking coupling and geometric radiation damping through the shared soil medium [2].

Liquefaction Hazards & Differential Settlement Consequences

Siting nuclear facilities on soft, saturated sandy soils is heavily constrained by liquefaction hazards. SRA safety reviews (such as those performed for the Paks NPP in Hungary) emphasize that liquefaction initiation during extreme earthquakes triggers localized volumetric strains, pore water pressure buildup, and bearing capacity degradation [3]. Deterministic and probabilistic slope and foundation assessments indicate that the primary hazard is post-liquefaction differential ground settlement rather than uniform settlement [3, 16]. Differential settlements cause building tilting, relative structural displacement, and severe stress concentration at critical structural nodes. Even minor tilting of a massive containment building can shear subterranean Essential Service Water (ESW) pipelines and power cables crossing the structure-subgrade interface, disabling emergency reactor core cooling and containment systems [3].

Advanced Seismic Isolation Systems

To mitigate these multidimensional dynamic demands, modern nuclear geotechnics has introduced advanced dynamic isolation systems. Conventional base isolation employs High-Damping Rubber Bearings (HDRB) to isolate horizontal ground motions, but remains vulnerable to vertical accelerations. To solve this issue, Liu et al. (2024) proposed a hybrid, multi-dimensional passive control system that combines three-dimensional base isolation with geotechnical seismic isolation (GSI). The system utilizes series-connected HDRBs and Combined Disc Springs with Friction (CDSB) to provide robust vertical and horizontal isolation. This is coupled with a 12 m thick Geotechnical Seismic Isolation layer composed of Rubber-Soil Mixtures (RSM) arranged directly beneath the base mat (G_{max} = 7.5 MPa, density ρ = 950 kg/m³ and initial damping ratio ζ = 4.5%) [17]. Under extreme three-dimensional shaking, this hybrid GSI system significantly dampens horizontal and vertical acceleration demands, dramatically reducing floor response spectra across the superstructure without increasing the critical displacement demands on the isolation bearings [17].

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

The fundamental geotechnical integration of Pillar I (chemo-mineralogical design) and Pillar II (macro-dynamic structural demand) reveals three critical scientific and conceptual tensions. Traditional geotechnical design assumes that raising subgrade mechanical properties is universally beneficial. However, evaluating deep-mixing ground improvement from a coupled, multi-scale perspective demonstrates that material-level chemical optimizations can directly compromise macro-dynamic seismic performance.

The Impedance-Stiffness Tension

Materials chemistry aims to maximize the shear strength (q_u) and shear modulus (G) of stabilized soils by optimizing pozzolanic and geopolymeric binder chemistry, resulting in a substantial increase in the shear wave velocity (Vs) of the stabilized block. However, dynamic finite element analyses [2] reveal that block-type DSM subgrade stiffening does not always improve seismic performance, and in many scenarios can actively amplify structural accelerations. The underlying physical mechanism is twofold. First, constructing a massive, stiffened DSM block beneath the reactor base mat shifts the fundamental frequency of the Soil-Foundation-Structure (SFS) system. If this shifted frequency overlaps with the dominant frequency content of the earthquake or the natural frequency of the containment superstructure, resonance occurs. Second, elevating the subgrade stiffness increases the wave impedance ($Z = \rho V_s$) contrast between the treated DSM zone (Vs = 1300 m/s) and the surrounding natural sand (Vs = 150 to 720 m/s) [2]. This impedance mismatch triggers complex wave propagation phenomena, including partial-wave reflection, wave-path distortion, and dynamic energy trapping within the foundation-DSM system. Consequently, DSM block-type ground improvement can dramatically amplify horizontal and vertical structural accelerations and concentrate seismic energy in narrow bands, exacerbating rocking-induced gapping and interface uplift [2].

Decadal Lifecycle vs. Coastal Aggressiveness

Critical nuclear facilities are designed for exceptionally long operational lifespans (typically 60 to 100 years) and are frequently located in aggressive coastal environments to secure access to cooling water intake [4].

This exposes the deep-mixing subgrade columns to highly corrosive groundwater containing elevated concentrations of sodium and magnesium sulfates. Under traditional calcium-based cementitious DSM stabilization, this triggers decadal ettringite decay, leading to microcracking, decadal strength loss, and complete structural disintegration [9, 14]. This establishes a critical multiscale feedback loop: the long-term geodynamic stability of the nuclear containment superstructure is completely dependent on the materials-level chemical durability of the binder. Therefore, selecting sulfate-resistant, slag-blended geopolymers is not merely a sustainable alternative, but a safety-critical prerequisite. It ensures that the shear modulus (G) and S-wave velocity (Vs) of the DSM block do not degrade chemically over the facility's decadal operational lifecycle [14].

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

In laboratory settings, materials scientists achieve highly optimized pozzolanic and geopolymeric binders through precise control of chemical molarities, exact liquid-to-solid ratios, and highly controlled curing environments [10]. bulk translating these formulations to field-scale Deep Soil Mixing in high-consequence nuclear projects introduces severe challenges. Nuclear regulatory reviews (such as NUREG-0800) mandate exceptionally high material homogeneity and strict Nuclear Quality Assurance (QA) standards [7]. The intrinsic spatial and chemical variability of recycled industrial and agricultural waste products—such as fluctuating amorphous silica fractions in fly ash or ground glass—makes standardizing field-scale deep mixing operations exceptionally difficult. Fulfilling regulatory safety margins requires a paradigm shift from lab-scale empirical optimization to advanced field monitoring, standardized manufacturing, and rigorous statistical uncertainty quantification (such as the 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 behavior of soil-foundation boundaries under extreme seismic excitation, we can integrate the philosophical framework proposed by Massimo Cacciari [1]. In his ontological treatise, Cacciari distinguishes between two concepts of the boundary: the limes and the limen. The limes represents a rigid, enclosing wall—a closed barrier that encloses a uniform container, enforcing absolute isolation and preventing contact. In contrast, the limen is a threshold—a dynamic, open frontier that serves as a site of contact, relationship, transition, and mediation [1]. Historically, standard civil engineering design codes have treated the soil-foundation boundary as a limes. Numerical models are frequently formulated using fully bonded, linear-elastic interface nodes, enforcing absolute displacement continuity and preventing sliding, separation, or gapping. This rigid, enclosing limes model creates a physical fiction. By locking the interface, it ignores the physical reality of separation, generating excessive artificial stress concentrations at the base mat edges and overlooking the secondary high-frequency floor accelerations triggered by structural rocking [4].

Conversely, modelling the soil-foundation interface as an unbonded, geometrically nonlinear contact boundary transforms the interface into a mechanical limen—a dynamic threshold of transition and energy redistribution. Under extreme seismic overturning moments, the foundation mat is permitted to uplift and separate from the subgrade, shifting the fundamental vibration period of the Soil-Foundation-Structure system and dissipating extensive dynamic energy through friction and geometric radiation damping [4]. This physical limen behavior can be mathematically represented in finite element formulations (e.g., in ABAQUS or OpenSees) via the unilateral Kuhn-Tucker contact conditions. In the normal direction, the contact conditions govern gapping and normal stress:

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

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 enforce that either a physical gap exists ($g_n > 0$) with zero normal pressure ($\sigma_n = 0$), or the interface is in contact ($g_n = 0$) with compressive contact pressure ($\sigma_n \leq 0$), completely precluding physical penetration.

In the tangential direction, the interface is governed by Coulomb's friction law and the stick-slip contact mechanics, formulated as:

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

where τ is the shear traction vector, and μ is the friction coefficient. When $f < 0$, the interface is in a state of stick, enforcing absolute tangential displacement increment compatibility. When $f = 0$, dynamic sliding initiates, causing plastic slippage and extensive hysteretic energy dissipation. By formulating the soil-foundation interface as a contact-mechanics-driven limen, the subgrade ceases to be a passive container. Instead, it becomes an active, mediating threshold that redistributes dynamic stresses, broadens the system's vibration period, and buffers the containment superstructure against extreme seismic energy pulses [4].

Table 2: 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

While significant advancements have been achieved in both chemical stabilization (Pillar I) and structural geodynamics (Pillar II), developing resilient nuclear-grade subgrades requires addressing three primary research gaps that currently divide these fields.

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

Materials research typically analyzes binder mineralogy, phase transformations (C-S-H, N-A-S-H, C-A-S-H volume fractions), and chemical dissolution kinetics at the microscale using advanced laboratory characterization (XRD, TGA, SEM, and EDS) [8, 14]. Conversely, geodynamic numerical studies model the stabilized subgrade (such as DSM blocks) as homogeneous, isotropic linear-elastic continuum elements, completely ignoring microstructural chemistry and decadal physical-chemical decay [2]. Currently, there is no quantitative mathematical link bridging these scales. Microstructural microcracks induced by wetting-drying cycles or chemical decomposition cannot be mapped directly into macro-scale dynamic parameters. To bridge this gap, future research should develop multiscale constitutive models, where microscale mineral volume fractions and porosity index evolution [10] serve as direct inputs to drive non-linear, pressure-dependent elasto-plastic soil models (such as the PDMY02 model in OpenSees) for dynamic SSI simulations.

Gap 2: Combined Chemo-Dynamic Testing Protocols

Existing experimental and numerical methodologies are heavily partitioned. Chemical durability and sulfate resistance studies submerge stabilized soil specimens in aggressive solutions for up to a year, but evaluate performance solely using static geomechanical tests (such as unconfined compression or direct shear) [14]. On the other hand, geodynamic research subjects foundations to extreme earthquake records in numerical simulations, but assumes pristine, chemically intact, and static soil properties throughout the seismic event [2]. The seismic and dynamic performance of chemically degraded, aged, or sulfate-attacked stabilized soils remains completely unexplored. Addressing this requires establishing combined chemo-dynamic testing protocols. Sustainable stabilized soil specimens must be subjected to accelerated chemical aging and subsequently evaluated using dynamic cyclic triaxial testing and centrifuge physical modeling. This is vital to capture the coupled, non-linear effects of environmental chemical decay and extreme seismic shaking.

Gap 3: Standardized Regulatory QA and Green Binder Guidelines

Nuclear safety guidelines and regulatory approval codes (such as USNRC NUREG-0800, IAEA NS-G-3.6, and ASCE 4-16 [15]) provide strict constraints on critical subgrade preparation, heavily favoring conventional, well-tested materials like compacted soil-cement or roller compacted concrete (RCC) backfills [7]. Because green binders (geopolymers, CCR-FA, and agricultural wastes) feature high chemical and physical variability depending on the waste source, they lack standardized, public long-term field performance data. To facilitate regulatory approval for green foundations, future research must establish a standardized database, formulate public manufacturing guidelines for waste-based binders, and draft specific design guidance within the framework of ASCE and IAEA nuclear safety standards.

VI. Conclusions

This state-of-the-art review has synthesized the critical, multiscale intersection of materials chemistry and structural geodynamics in soil stabilization for critical nuclear infrastructure. The primary findings are summarized as follows:

1. A truly resilient geotechnical design for critical facilities cannot treat binder materials chemistry and macro-structural dynamics as isolated disciplines. The long-term dynamic safety margins of the nuclear superstructure are completely dependent on the materials-level chemical durability of the foundation subgrade [2, 14].
2. Deep Soil Mixing represents a double-edged sword. While pozzolanic and geopolymeric binder chemistry dictates macro-scale compressive strength (qu) and chemical durability against coastal sulfate attack, the resulting mechanical stiffening alters the wave impedance ($Z = \rho Vs$) contrast of the site, which can trap seismic waves, focusing energy and amplifying horizontal and vertical structural accelerations [2].
3. The soil-foundation boundary under extreme seismic loading operates as a dynamic threshold (limen), rather than a rigid partition (limes). Formulating contact boundaries using Kuhn-Tucker complementarity conditions allows the containment building to separate, slide, and rock, shifting the fundamental vibration period and protecting internal power-generation mechanical equipment from rigid stress concentrations [1, 4].
4. To advance this field, researchers must develop multiscale coupling models linking micro-mineralogical transformations directly to nonlinear continuum plasticity formulations. We must establish combined chemo-dynamic experimental protocols (such as cyclic triaxial testing of chemically aged geopolymer soils) and formulate standardized regulatory guidelines to pave the way for green, waste-derived binders in high-hazard siting [2, 14].

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