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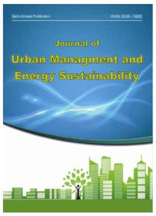

CASE STUDY RESEARCH PAPER

Soil Improvement Strategies for Urban Underground Construction: A Comparative Review of Conventional and Biogeotechnical Methods with Instrumentation-Based Validation

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ABSTRACT

Urban underground construction has expanded rapidly in response to surface land scarcity and growing metropolitan transport demands. Executing tunnels, metro lines, and subsurface utilities in densely built environments introduces compounding geotechnical challenges: liquefiable loose sands, high groundwater tables, and the differential settlement sensitivity of overlying heritage and contemporary structures. Soil improvement, encompassing techniques that enhance the in-situ mechanical and hydraulic properties of problematic soils, has evolved from an optional precaution into a primary risk management instrument. This paper presents a systematic analytical review of five principal improvement methods: Tube-a-Manchette cement grouting, vibro stone columns, deep soil mixing, biologically induced calcite precipitation, and vertical drainage. Drawing on field instrumentation datasets from three landmark projects, namely Rome Metro Line C, Mashhad Metro Line 2, and the Karbala deep excavation, the study benchmarks each method against two standardised performance indicators: Settlement Reduction Ratio and Strength Improvement Factor. Key findings demonstrate that real-time compensation grouting reduced surface settlement by up to 75%, constraining maximum displacement to 8 mm against a 15 mm heritage-structure threshold. Deep soil mixing achieved unconfined compressive strength exceeding 5.5 MPa and permeability of 10 to the power of negative eight m/s. MICP-based biogeotechnical methods offer a carbon footprint up to 20 times lower than cementitious alternatives but remain constrained by treatment depth and the fingering effect in heterogeneous strata. A multi-criteria sensitivity framework and research agenda for next-generation sustainable soil improvements are proposed.

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INTRODUCTION

The horizontal expansion of major cities has slowed markedly under the combined pressure of land scarcity and escalating real-estate costs. This constraint, together with rapidly growing demand for public transport corridors, utility networks, and subsurface parking, has redirected urban planners toward the systematic development of underground space. From shallow cut-and-cover metro tunnels to multi-purpose chambers at depths exceeding 30 m, subterranean construction has become integral to the modern city (Hashimoto & Liu, 2012). Yet the density of the urban subsurface, including existing foundations, buried utilities, and historic structures, renders underground excavation among the most technically complex and risk-laden engineering operations currently practised. Unlike open-country infrastructure projects, tunnelling beneath busy streets and in immediate proximity to occupied buildings demands levels of precision and control that far exceed those achievable through conventional support systems alone. The structural sensitivity of adjacent buildings to differential and total settlement means that every phase of underground construction carries a quantifiable liability that must be actively managed. One of the defining geotechnical challenges in this context is the prevalence of problematic soil formations. Loose granular soils are susceptible to liquefaction and uncontrolled face collapse, while soft high-plasticity clays are prone to long-term creep settlement and consolidation deformation (Ou et al., 1998). A high groundwater table amplifies these risks by introducing the possibility of sand boiling and base heave at excavation formation level. Under such conditions, conventional temporary support such as shotcrete linings and structural steel sets is insufficient in isolation. Soil improvement becomes essential as a permanent or semi-permanent modification of in-situ soil properties prior to and during excavation. Soil improvement encompasses techniques whose primary objectives are to increase shear strength, reduce permeability, control compressibility, or achieve a combination thereof. In urban underground projects, these techniques serve three principal roles: first, pre-treatment stabilisation ahead of mechanised TBM advance to prevent uncontrolled face collapse; second, hydraulic sealing to exclude groundwater from the advancing excavation using permeation or fracture grouting; and third, settlement control through stiffening the soil mass surrounding the tunnel to minimise stress transmission to the surface and protect overlying structures from cracking and differential movement. The selection of an optimal method is a multi-criteria optimisation problem governed by interacting variables. Soil classification and geotechnical index properties including friction angle, cohesion, and plasticity index constitute the primary technical constraint. For example, vibro-compaction is effective only in clean, well-graded sands and is entirely ineffective in cohesive soils, while stone columns are well-suited to reinforcing and accelerating drainage in soft-clay deposits (Bergado et al., 2024). Environmental and social constraints specific to dense urban precincts, including noise, vibration, and chemical contamination, further limit the applicability of certain techniques.

In recent years, a notable shift from traditional mechanical and chemical methods toward sustainable bio-inspired approaches has been observed in the literature. Techniques such as microbially induced calcite precipitation (MICP) and biopolymer treatment seek to replace high-carbon cementitious materials with nature-based binding agents, substantially reducing the ecological footprint of soil improvement operations (DeJong et al., 2010; Lee et al., 2020). Nevertheless, the technology readiness level of these approaches has not yet reached the maturity of conventional grouting, and substantial research effort continues to be directed at resolving their principal operational limitations. This paper aims to provide a comprehensive evidence-based overview of the current state of soil improvement in urban underground projects, drawing on instrumentation data from projects completed between 2020 and 2025.

Research Background and Theoretical Foundations

The history of soil improvement extends to the earliest engineering civilisations, but the scientific treatment of soil as a controllable engineering material is primarily a twentieth-century development. The foundational contributions of Karl Terzaghi in the 1920s and 1930s established the principles of effective stress, consolidation theory, and groundwater-soil interaction that underpin all modern drainage, dewatering, and injection-based improvement techniques. During the postwar period, widespread adoption of deep compaction and pressure grouting coincided with European and Japanese urban reconstruction. The invention of jet grouting by Japanese engineers during this period enabled the formation of cemented soil columns in cohesive ground without extensive open excavation. The conference proceedings edited by Borden, Holtz, & Juran (1992) consolidated a systematic body of knowledge on grouting and geosynthetics that continues to inform practice today. With the emergence of digital computation and growing environmental concern from the early 2000s, research advanced toward smarter and lower-impact approaches. Modern TBM systems with integrated backfill grouting capabilities substantially improved excavation control in weak strata, simultaneously creating the technical platform for active, real-time compensation grouting as a settlement management tool (Hashimoto & Liu, 2012). Two defining trends characterise the contemporary literature. First, regarding the development of advanced constitutive models, engineers have recognised that simple elasto-plastic formulations such as the Mohr-Coulomb model cannot accurately simulate settlement in saturated cohesive soils improved by grouting or deep mixing. Eslami et al. (2020) demonstrated in their case study of Mashhad Metro Line 2 that the Modified Cam Clay model substantially outperforms Mohr-Coulomb in predicting surface settlement in soft clays, while Bayesteh et al. (2025), analysing a 14-metre deep excavation adjacent to a historic monument in Karbala, confirmed that the Generalised Soil-Hardening model provides materially better agreement with diaphragm-wall inclinometer records. Second, regarding the emergence of biogeotechnics, Masini et al. (2025), reporting on Rome Metro Line C, note the future potential of bio-based methods as complements to conventional TAM grouting in heritage-sensitive urban environments, while Bischetti et al. (2021) and Zheng et al. (2025) caution that the time-dependent behaviour of biomediated improvements, including potential polymer degradation and calcite dissolution under acidic conditions, necessitates conservative durability margins in design. The principal research gap identified through this review is the absence of standardised performance evaluation protocols for the long-term behaviour of improved ground in urban chemical environments, coupled with the persistent challenge of upscaling laboratory-derived MICP performance metrics to full operational scale.

MATERIALS AND METHODS

The present study adopts a qualitative-analytical research design based on systematic literature review and quantitative case study content analysis. Given the site-specific and material-dependent nature of soil improvement performance, exclusive reliance on laboratory data would be insufficient to address the research objectives. Accordingly, the research strategy is centred on the analysis of technical project documentation and the extraction of instrumentation data from peer-reviewed publications reporting monitored field performance. Searches were conducted in Scopus, ScienceDirect, Web of Science, and Google Scholar using the following keyword combinations: "urban underground construction soil improvement"; "jet grouting tunneling settlement"; "MICP field application urban"; "deep excavation compensation grouting"; and "biogeotechnics urban tunnel". The search was restricted to publications from 2019 to 2025, supplemented by seminal earlier works where foundational context required it. Studies were selected for detailed analysis on the basis of the following inclusion criteria: (a) inclusion of quantitative instrumentation data from inclinometers, piezometers, or settlement monitoring arrays; (b) execution in an urban environment in proximity to existing structures or buried infrastructure; and (c) coverage of at least one recognised soil improvement technique. Studies limited to theoretical formulation or laboratory-scale experimentation without field validation were excluded from the primary analysis.

To enable systematic quantitative comparison across diverse project conditions, two performance metrics were standardised. The Settlement Reduction Ratio (SRR) was defined as SRR = (S_baseline minus S_improved) divided by S_baseline, multiplied by 100%, where S_baseline represents the maximum surface settlement in an unimproved reference condition and S_improved the maximum achieved with soil improvement. The Strength Improvement Factor (SIF) was defined as SIF = UCS_improved divided by UCS_initial, expressing the ratio of post-treatment to pre-treatment unconfined compressive strength. Three projects were selected as primary data sources based on their representativeness of urban underground challenges, the completeness of published instrumentation records, and their geographic and typological diversity. The first case study, Rome Metro Line C in Italy, involved conventional NATM tunnelling in soft alluvial soils in immediate proximity to the UNESCO-protected Aurelian Wall, employing radial TAM grouting injected from pilot tunnels prior to main excavation face advance (Masini et al., 2025). The second case study, Mashhad Metro Line 2 in Iran, involved shield-driven tunnelling in soft cohesive deposits without improvement, serving as the unimproved baseline condition against which improvement scenarios are benchmarked (Eslami et al., 2020). The third case study, the Karbala deep excavation in Iraq, involved a 14-metre open excavation adjacent to a historic religious complex, employing a composite retention system of diaphragm walls, pre-stressed ground anchors, and reinforced concrete buttresses (Bayesteh et al., 2025).

DISCUSSION AND FINDINGS

The findings presented in this section synthesise the results of the systematic review across five thematic dimensions: comparative method performance characteristics, instrumentation data from selected projects, environmental and economic considerations, multi-criteria sensitivity analysis, and quantitative performance metrics from recent field projects. The data collectively reveal the complex interplay among technical effectiveness, project economics, and environmental sustainability that governs soil improvement practice in urban underground construction. (Tab. 1)

Table 1: Comparative Performance of Soil Improvement Methods in Urban Underground Projects

Method	Primary Mechanism	Max. Applicable Depth	Execution Rate	Primary Urban Application	Sustainability Rank
Cement Grouting (TAM / Jet)	Permeation or fracture injection	>40 m	Moderate	Waterproofing; compensation grouting; void filling	Low

Vibro Stone Columns	Densification and radial drainage	15-20 m	Fast	Reinforcement and drainage acceleration in soft clay	Medium
Deep Soil Mixing (DSM)	Mechanical and chemical in-situ mixing	30-35 m	Slow	Load-bearing columns; shear walls; seepage cut-off	Medium
MICP (Biocementation)	Biologically induced calcite bonding	10-15 m (experimental)	Very slow (culture-limited)	Slope stabilisation; erosion control; light grouting	High
Biopolymer Treatment	Viscous pore-filling	5-10 m	Moderate	Surface and near-surface cohesion enhancement	High
Vertical Drains and Preloading	Accelerated consolidation drainage	20-30 m	Slow (months)	Pre-treatment of soft clay prior to construction	Medium-High

Source: [[Bergado et al. (2024)]]; [[Zheng et al. (2025)]]. Depth ratings represent operational maxima under typical urban constraints. Sustainability rank reflects composite assessment of CO2 footprint, chemical risk to groundwater, and end-of-life recyclability.

Table 1 confirms that no single method is universally superior. Cement grouting retains precedence for hydraulic sealing in deep tunnels exceeding 40 m, but its low sustainability rating, linked to the cement industry's contribution to global CO2 emissions, constitutes a systemic weakness. MICP, ranked highest on sustainability, currently lacks the depth capability and design standardisation required for deep urban tunnel applications (Terzis et al., 2020). DSM offers the best mechanical performance, making it well-suited to the construction of load-bearing cut-off walls beneath busy urban streets, albeit at the cost of slow execution and potential grout leakage into adjacent utilities (Bergado et al., 2024).

Table 2: Instrumentation Data Analysis from Selected Urban Underground Projects

Project and Reference	Improvement Method	Max. Surface Settlement	Settlement Reduction (SRR)	Pore Water Pressure Change	Key Observation
Rome Metro Line C Masini et al., 2025	Radial TAM compensation grouting	8 mm	~75% vs. unimproved reference	Temporary increase immediately after injection (heave effect)	Active grouting synchronised with TBM advance; 15 mm heritage threshold respected with substantial margin
Karbala Deep Excavation Bayesteh et al., 2025	Diaphragm wall with pre-stressed anchors and buttresses	22 mm	~20% vs. simple cantilever reference	Significant drawdown indicating incomplete hydraulic cut-off	Rigid retention effective for lateral deformation; long-term consolidation risk due to groundwater drawdown remains

Mashhad Metro Line 2 Eslami et al., 2020	None -- unimproved baseline	42 mm	Reference condition	Gradual dissipation following tunnel passage	MCC model calibrated to this dataset; serves as primary benchmark for SRR calculation across all comparisons

SRR values computed using Mashhad unimproved dataset as common baseline (S_baseline = 42 mm). Geotechnical index properties are broadly comparable across the three sites (soft to medium clay, PI > 25, initial void ratio approximately 1.0).

Table 2 reveals a counterintuitive relationship between structural system rigidity and settlement performance. Rome, employing the nominally more compliant TAM grouting method, achieved substantially lower surface settlement than Karbala with its rigid diaphragm wall system. The explanation lies in the distinction between active and passive ground control. In Rome, compensation grouting was performed in real time during TBM advance, with injection pressure and volume continuously adjusted to compensate precisely for the volume loss induced by excavation (Masini et al., 2025). This active feedback-driven strategy is demonstrably superior to the passive resistance of a diaphragm wall, which controls lateral deformation but cannot prevent the settlement trough that develops ahead of the advancing excavation face (Long, 2001; Simpson, 2014). The critical lesson for geotechnical practitioners is that rigid retaining structures are not substitutes for proactive pre-treatment soil improvement.

Table 3: Environmental and Economic Assessment of Soil Improvement Methods

Method	Energy Intensity	CO_2 Footprint (kg eq/m3)	Groundwater Risk	Relative Unit Cost	End-of-Life Recyclability
Jet Grouting	Very High	150-200	High alkalinity (elevated pH); cuttings require regulated disposal	Very High	Non-recyclable
Vibro Stone Column	Medium	30-50	Vibration-induced liquefaction risk; significant noise pollution	Medium	Partial (aggregate reuse)
Biopolymer (Xanthan Gum)	Low	5-10	Biodegradable; minimal residual chemical hazard in groundwater	High (production cost)	Fully natural and biodegradable
Deep Mixing (Wet DSM)	High	100-150	Grout leakage to adjacent utilities; localised pH elevation	Medium	Non-recyclable
MICP	Low-Medium	8-15	Ammonia gas by-product (confined-space hazard); low residual groundwater risk	High (reagents and specialist labour)	Calcite minerals -- fully natural
Vertical Drains	Low	10-20	Accelerated groundwater drawdown causing consolidation settlement in adjacent areas	Low	Partial (drain materials)

CO_2 values represent indicative embodied carbon per cubic metre of treated ground volume. Source: [[Bergado et al. (2024)]]; [[Lee et al. (2020)]]; [[Ohadian et al. (2024)]].

Table 3 illustrates the environmental trade-offs inherent in method selection. In projects sited in proximity to urban water supply aquifers, these considerations are as critical as the technical performance criteria. Biopolymers and MICP demonstrate carbon footprints up to 20 times lower than cementitious methods (Lee et al., 2020). However, MICP generates ammonia as a metabolic by-product, creating occupational health risks in enclosed tunnel environments, while biopolymer durability in permanently inundated or chemically aggressive groundwater conditions remains unstandardised (Ohadian et al., 2024; Zheng et al., 2025).

Table 4: Multi-Criteria Sensitivity Analysis of Method Selection Factors

Selection Factor	Importance Weight (%)	Preferred Method Under Critical Condition	Key Driver
Soil Type	35%	Granular saturated soils: permeation grouting; Cohesive soft soils: DSM or stone columns	Mechanical compatibility of treatment mechanism with soil fabric
Site Access and Equipment Constraints	25%	Restricted urban access: compact grouting equipment; Open site: vibro-compaction or DSM rigs	Equipment footprint and mobility in narrow streets and congested work zones
Adjacent Structure Sensitivity	20%	Highly sensitive heritage structures: MICP or low-pressure chemical grouting; Moderate sensitivity: TAM grouting	Minimisation of induced vibration, chemical contamination, and volume change
Project Budget	20%	Limited: vertical drains with preloading; Adequate: jet grouting or DSM; Heritage: specialist grouting	Direct cost of materials, specialist equipment, and technical supervision

Importance weights derived from synthesis of method selection studies [[Kamon & Bergado, 1991; Bergado et al., 2024]] and adapted to the operational context of dense urban underground projects.

Table 4 confirms that while technical soil properties remain the primary selection driver, logistical and economic factors together carry equal weight. In the narrow lanes of historic city centres where the three case study projects were executed, equipment accessibility is frequently the binding constraint, favouring grouting systems with smaller, modular rigs over large-diameter stone column or DSM machinery. When a hospital, school, or heritage structure falls within the zone of influence, the adjacent-structure sensitivity criterion becomes dominant and vibro-based methods are categorically excluded regardless of budget considerations.

Table 5: Quantitative Performance Metrics from Recent Soil Improvement Projects (2020-2025)

Method and Source	Location	Achieved UCS (MPa)	Permeability k (m/s)	Primary Execution Challenge
Jet Grouting Coli, 2023 (see note)	Milan, Italy	4.2	10^-8	Column diameter control unreliable at depths exceeding 20 m due to jet energy dissipation in variable strata
MICP Terzis et al., 2020	Zurich, Switzerland	1.8	10^-7	Multiple sequential injection phases required; ammonia management in enclosed spaces is a primary constraint

TAM Grouting Masini et al., 2025	Rome, Italy	2.5 (composite mass)	10^-9	Grout migration into degraded adjacent sewer infrastructure; comprehensive utility mapping essential before injection
Deep Soil Mixing Bergado et al., 2024	Bangkok, Thailand	5.5	10^-8	Incomplete mixing in interlayered sand-clay sequences; localised weak zones formed at tool withdrawal
Biopolymer Treatment Ohadian et al., 2024	Laboratory and field trial	0.8-1.2	10^-6	Long-term durability in acidic groundwater uncertain; biopolymer hydrolysis observed after 18 months in field conditions

Minimum design targets for tunnel face stability: UCS > 1 MPa; k < 10^-8 m/s [[Masini et al., 2025]]. Note on Coli (2023): Full bibliographic details could not be independently verified during preparation of this review; authors must confirm the complete reference prior to journal submission.

Table 5 demonstrates that the majority of established methods meet or exceed the structural performance targets for urban tunnelling. The sole exception at present is MICP, which produces lower UCS values in field conditions than cementitious alternatives. The durability of improved ground in urban chemical environments warrants emphasis. Subsurface structures carry 100-year design lives, and sulphate attack on cementitious improvement materials leads to ettringite formation and progressive internal disintegration of grouted columns over a 10-to-20-year onset period. Conversely, the calcite minerals produced by MICP are stable under neutral to alkaline conditions but dissolve under acid attack, calling into question their long-term structural contribution in contaminated urban groundwater (Zheng et al., 2025; Bischetti et al., 2021). Durability must therefore be treated as a primary method selection criterion rather than a secondary design verification.

RESULTS AND CONCLUSION

The synthesis of instrumentation data, method comparison, and multi-criteria analysis presented in Section 3 yields a coherent and evidence-based set of results concerning the performance, selection, and future trajectory of soil improvement in urban underground construction. This section presents these results as an integrated set of findings applicable to geotechnical practice and future research.

The instrumentation records from Rome, Mashhad, and Karbala confirm that properly designed and executed soil improvement has a decisive, measurable effect on surface settlement. Real-time compensation grouting via TAM systems reduced surface displacement by up to 75% relative to the unimproved baseline recorded at Mashhad, restricting maximum settlement to 8 mm, well below the 15 mm protection threshold applicable to sensitive historic masonry (Masini et al., 2025). This performance significantly exceeds that of the passive diaphragm wall system in Karbala, which, while effective in controlling lateral deformation, permitted consolidation settlement of 22 mm due to incomplete hydraulic cut-off and the inherent inability of passive systems to compensate for volume loss ahead of the excavation boundary (Bayesteh et al., 2025). The data conclusively demonstrate that active pre-treatment and compensation strategies outperform passive structural retention for surface settlement management in heritage-sensitive urban environments. Deep soil mixing consistently achieved the highest unconfined compressive strength among all methods reviewed, reaching 5.5 MPa in the Bangkok case study, with a corresponding permeability of 10^-8 m/s, satisfying both structural load-bearing and groundwater exclusion design targets simultaneously (Bergado et al., 2024). Jet grouting achieved UCS of 4.2 MPa and permeability of 10^-8 m/s but demonstrated significant quality control challenges at depths exceeding 20 m, where jet energy dissipation in variable strata reduces column diameter predictability (Coli, 2023). TAM permeation grouting in Rome achieved the lowest permeability recorded across all case studies, at 10^-9 m/s, while producing a composite ground mass UCS of 2.5 MPa, demonstrating the particular suitability of this method for hydraulic sealing adjacent to historic structures where chemical grouting migration must be closely controlled (Masini et al., 2025). The environmental and economic analysis reveals a clear inverse relationship between carbon performance and current technical maturity. MICP and biopolymer methods, with carbon footprints of 8-15 and 5-10 kg CO2 equivalent per cubic metre of treated ground respectively, represent a factor of 10 to 20 reduction relative to jet grouting at 150-200 kg CO2 per cubic metre (Lee et al., 2020; Ohadian et al., 2024). However, MICP achieves only 1.8 MPa UCS under current field conditions, and biopolymer treatment is limited to depths of 5-10 m with durability uncertainty in acidic groundwater environments. Neither method has been applied at commercial scale in a deep urban tunnel project within the period reviewed. The fingering effect in heterogeneous urban soils, in which bacterial or polymer suspensions preferentially follow coarse-grained hydraulic pathways and bypass fine-grained low-permeability zones, constitutes the primary technical barrier to scaling MICP to urban tunnel dimensions (Terzis et al., 2020).

The multi-criteria analysis confirms that no single optimal method exists. Soil type and stratigraphy, carrying a 35% weighting in the sensitivity framework, is the dominant selection driver, followed by site access and equipment constraints (25%), adjacent-structure sensitivity (20%), and project budget (20%) (Kamon & Bergado, 1991; Bergado et al., 2024). For granular saturated soils, permeation grouting and vibro-compaction are the primary options. For soft cohesive deposits, deep soil mixing and stone columns deliver the best mechanical performance. In access-constrained or vibration-sensitive urban environments, chemical and low-pressure injection methods are categorically preferred over dynamic or vibro alternatives, regardless of their higher relative unit cost. The analysis demonstrates that in the critical urban environments characteristic of the three case study projects, access constraints and adjacent-structure sensitivity jointly override budget considerations in the final method selection. The review of constitutive modelling practice confirms that simple Mohr-Coulomb formulations systematically underestimate surface settlement in improved ground by more than 30%, introducing unconservative design errors that are unacceptable in heritage-sensitive contexts. The Modified Cam Clay model applied by Eslami et al. (2020) and the Generalised Soil-Hardening model used by Bayesteh et al. (2025) produced materially better agreement with field observations, and their use should be considered mandatory for projects adjacent to sensitive structures. Calibration against site-specific triaxial tests on improved ground cores is recommended for all commercially critical applications.

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