



ADVANCED METHOD OF SUBSOIL IMPROVEMENT IN COMPLEX GEOTECHNICAL CONDITONS

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ABSTRACT

Subsoil improvement is essential in geotechnical engineering to ensure stability and performance in challenging ground conditions. This paper presents a comprehensive review of advanced subsoil improvement techniques applicable in complex geotechnical conditions. The study categorizes surface and deep improvement methods, evaluates their mechanisms, and outlines selection criteria based on soil type, groundwater, loading, and sustainability factors.

1. Introduction

Construction in challenging geotechnical environments demands subsoil improvement techniques to ensure safety, durability, and economic efficiency [3]. Natural soils often fail to meet design criteria due to:

- insufficient bearing capacity,
- excessive compressibility, or
- heterogeneous layering.

Ground improvement enables the use of such soils by enhancing their strength, stiffness, and deformation characteristics. Recent decades have witnessed significant advances in both surface and deep ground improvement technologies [55]. These methods vary in mechanism, depth of influence, construction complexity, and environmental footprint [1]. Mechanical methods, such as compaction or preloading, are widely used for shallow applications [7, 46]. Chemically-based techniques, including lime, cement, and fly ash stabilization, offer durable performance in fine-grained or organic soils [11, 76]. Geosynthetics such as geotextiles and geogrids are increasingly adopted to reinforce weak subgrades and enhance stability [44, 50]. Geopolymers represent a new frontier in soil stabilization, as they can reduce the amount of cement used in these applications [27, 80].

Deep improvement techniques—such as jet grouting, deep soil mixing (DSM), stone columns, and rigid inclusions—target weak or compressible soils at greater depths and under high load demands [4, 35]. The selection of a suitable technique depends on a range of technical and site-specific factors.

This paper reviews the types of subsoils requiring treatment, outlines the criteria guiding method selection, and presents a comparative overview of the most widely adopted improvement technologies.

2. Subsoil Types and the Need for Improvement

Subsoils can be broadly categorized into granular soils, cohesive soils, organic soils, and peat, each exhibiting distinct geomechanical behaviors that influence their suitability for construction and the need for improvement:

- Granular soils (sands and gravels): These soils typically possess high shear strength and low compressibility, offering good bearing capacity. However, when loosely compacted, they are prone to settlement and liquefaction under dynamic loads. Improvement may involve compaction or grouting to increase density and reduce potential displacement [54, 74].
- Anthropogenic soils (Construction and Demolition materials and Industrial Solid Wastes): These soils typically consist of highly heterogeneous materials with variable particle sizes, compositions, and engineering properties. Due to their origin, they often exhibit inconsistent shear strength [28], compressibility [29], and bearing capacity [66]. Some components (e.g., recycled concrete aggregate or blast furnace slag) may provide reasonable stability [34], while others (e.g., organic debris or lightweight industrial waste) can lead to excessive settlement or weak structural support [70].



Geotechnical challenges include unpredictable behavior under cyclic excitation [67–69], potential for chemical reactivity, and susceptibility to erosion, permeability issues or leaching [32, 65]. Improvement methods may involve sorting, stabilization (e.g., cementitious binders), or encapsulation to enhance uniformity and strength [60].

- Cohesive soils (clays and silts): Characterized by low permeability and high plasticity, cohesive soils are sensitive to moisture changes. Their behavior under load is complex, with delayed settlement due to consolidation and potential for shrink-swell cycles. Additionally, the effect of traffic loading often leads to excess pore water pressure generation [30, 31, 33]. Stabilization or deep mixing is often applied to enhance their strength and reduce deformation [4, 37].
- Organic soils: Composed of decomposed vegetation, these soils are highly compressible, have very low shear strength, and may produce aggressive chemical environments [64, 77]. They present significant challenges for construction, typically requiring removal or treatment with deep improvement methods such as stone columns or rigid inclusions.
- Peat: Peat soils consist of a high organic content with extreme compressibility and very low load-bearing capacity. They exhibit unpredictable settlement behavior and are difficult to compact or stabilize effectively [43, 63]. Deep techniques like dynamic replacement or rigid inclusions are usually necessary.

Improvement is necessary when natural soils cannot meet project-specific criteria for bearing capacity, settlement control, or stability. These challenges are particularly prevalent in infrastructure projects in coastal, or reclaimed land areas. Ground modification enables the use of such problematic sites, ensures structural integrity, and minimizes long-term maintenance or failure risks [13].

3. Selection Criteria and Application in Complex Conditions

Selecting an appropriate subsoil improvement technique is a critical step in geotechnical design and is guided by several technical, environmental, and economic considerations:

- Soil type and geotechnical properties: The nature of the subsoil is the primary determinant. For example, loose sands respond well to compaction, whereas soft clays benefit more from vertical drains or deep soil mixing [14, 62]. Peaty and organic soils often necessitate rigid inclusions or complete soil replacement.
- Groundwater conditions: The presence of a high water table can limit the effectiveness of certain chemical methods and increase the complexity of construction. In such cases, methods like jet grouting, vibro-replacement, or preloading with vertical drains are favored [17, 22].
- Required depth of improvement: Surface improvement techniques are typically limited to depths of 1–3 meters and are ideal for road subgrades and shallow foundations [15, 38]. In contrast, deep techniques like DSM or stone columns can reach depths of 20–30 meters or more, suitable for high-rise structures or embankments on soft soils.
- Structural and load requirements: Projects involving heavy structures, bridges, or storage tanks may demand high bearing capacity and low settlement tolerance, favoring rigid inclusions, micropiles, or jet grouting. For lighter loads, surface stabilization or geosynthetic reinforcement may suffice [18, 21].
- Construction schedule and site limitations: Tight construction schedules may limit the use of time-dependent techniques such as preloading. Similarly, urban environments may restrict noisy or vibration-intensive methods, necessitating low-impact alternatives like chemical stabilization or jet grouting [12, 79].
- Environmental and sustainability concerns: The use of industrial by-products (e.g., fly ash) in chemical stabilization or recycled materials in dynamic replacement contributes to more sustainable ground improvement practices [9, 58, 72]. Environmental risk assessments also influence method selection, especially in sensitive ecosystems [45, 61].



These criteria are typically assessed through geotechnical investigations, laboratory tests, and numerical modeling [23, 48, 71]. In many cases, a hybrid or staged approach is adopted—combining techniques such as preloading with vertical drains and surface stabilization to achieve both economic and technical efficiency.

Table 1: Comparative overview of surface and deep improvement methods by application criteria.

Method	Depth Range	Suitable Soils	Main Benefits	Limitations	Typical Applications
Compaction [6, 16]	0–3 m	Granular soils	Increased density and strength	Ineffective in cohesive soils	Road subgrades
Chemical Stabilization [24, 56]	0–2 m	Clays, silts	Improved strength and durability	Not suitable in high groundwater	Foundations, embankments
Geosynthetics [40, 51]	0–1 m	Various	Reinforcement and separation	Limited depth effect	Roads, slopes
Deep Soil Mixing [20, 35]	5–30 m	Soft clays, silts	Strengthens weak soils	Special equipment needed	Foundations, containment
Jet Grouting [39]	5–40 m	Wide range	Precise and strong treatment	High cost	Underpinning, cutoff walls
Stone Columns [8]	3–25 m	Soft clays, silts	Improved drainage and load capacity	Not for very soft soils	Tanks, embankments
Rigid Inclusions [82]	5–30 m	Organic, peat, soft soils	Load transfer, minimal settlement	Complex design	Slabs, heavy structures

4. Surface Improvement Techniques

Surface improvement techniques are used to enhance the properties of the upper soil layers, typically to a depth of 1–3 meters. These methods are most effective for improving subgrades beneath pavements, embankments, and shallow foundations. The key surface improvement techniques include mechanical compaction, preloading and surcharge, chemical stabilization, and geosynthetic reinforcement.

4.1 Mechanical Compaction

Compaction increases the density of granular soils, reducing void ratio and improving shear strength and stiffness. Methods include static rollers, vibratory compactors, and impact rollers. Static compaction involves the use of heavy rollers or tamping equipment to apply pressure to the ground surface, suitable for granular soils at shallow depths [42, 83]. Vibro-compaction uses vibratory probes or surface vibrators to rearrange soil particles into a denser configuration [59]. This technique is effective in clean, saturated sands and gravels. Dynamic compaction involves dropping heavy weights (typically 10–40 tonnes) from significant heights (up to 30 m) to induce shockwaves and compact soils to greater depths (up to 10 m) [73, 78]. This method is suitable for well-graded sands and gravels but less effective in cohesive or organic soils [41].

4.2 Preloading and Surcharging

Preloading involves placing a temporary load to induce settlement before construction [47]. It is often combined with vertical drains to accelerate consolidation in soft clays or organic soils (to shorten the drainage path). They facilitate horizontal drainage, thereby accelerating pore water dissipation. While time-consuming, it provides reliable long-term performance for structures sensitive to settlement [38, 81].



4.3 Chemical Stabilization

Stabilization using binders such as lime, cement, and fly ash modifies the soil structure, reducing plasticity and increasing strength [25]. Stabilization leads to pozzolanic reactions, forming cementitious compounds that bond soil particles. It is commonly applied in subgrade preparation for roads and runways. Lime is effective in clays with high plasticity, while cement is preferred for silty soils. Fly ash, as an industrial by-product, improves workability and sustainability [5, 10].

4.4 Geosynthetic Reinforcement

Geosynthetics—such as geotextiles, geogrids, and geocells—are increasingly used to reinforce soils. They enhance load distribution, reduce rutting, and control erosion. Applications include road bases, embankments on soft soils, and slope stabilization [19, 26].

5. Deep Improvement Techniques

Deep improvement techniques are employed when weak soils extend beyond the reach of surface methods or when significant load-bearing capacity and settlement control are required. These methods are suitable for deep foundations, embankments, and infrastructure over soft or compressible soils. Key techniques include:

5.1 Deep Soil Mixing (DSM)

Deep Soil Mixing involves blending in-situ soil with cementitious binders using rotating mixing tools. The result is a soil-cement matrix with enhanced strength and stiffness, especially when additional, dispersed reinforcement is introduced [52, 53, 53]. DSM is effective in soft clays, silts, and even organic soils [49]. It minimizes spoil generation and is often used for foundation support or ground containment structures [15].

5.2 Jet Grouting

Jet grouting utilizes high-pressure jets of grout to erode and mix the in-situ soil, forming columns of grouted material with high strength. It is applicable to a wide range of soils and can be used to form cutoff walls, underpin existing foundations, or stabilize slopes. Jet grouting is particularly useful in urban environments where precision and minimal disturbance are required [57].

5.3 Stone Columns

Stone columns (also known as vibro-replacement) involve the insertion of compacted aggregate into weak soils using a vibrating probe. This technique increases load-bearing capacity and accelerates consolidation in soft clays. It is widely used beneath embankments, tanks, and industrial facilities. Stone columns are cost-effective and environmentally friendly when using recycled aggregate [2].

5.4 Rigid Inclusions

Rigid inclusions are concrete columns installed in soft ground to transfer loads to deeper, stiffer strata. Unlike traditional piles, they do not rely on end bearing but work through load transfer to surrounding improved soil. This method is suitable for highly compressible soils such as peat or organic clay and is often used under slabs, embankments, or storage tanks [82].

5.5 Dynamic Replacement

Dynamic replacement combines the principles of dynamic compaction with the introduction of granular material into soft soils. Heavy weights dropped from height displace soil and form reinforced granular columns. This method is effective for heterogeneous or organic soils where other techniques may be less effective [75].



These methods differ in installation depth, soil compatibility, environmental impact, and cost. Their selection depends on project-specific requirements, including loading conditions, ground profile, site accessibility, and sustainability considerations.

6. Summary and Conclusions

This paper has reviewed the current state of surface and deep subsoil improvement techniques in complex geotechnical settings. It highlights the variability of subsoil types and the importance of selecting appropriate methods based on soil behavior, loading demands, groundwater conditions, and environmental constraints.

Surface improvement techniques such as compaction, chemical stabilization, and geosynthetic reinforcement are effective for shallow applications, particularly in granular or moderately cohesive soils. Deep improvement methods—including DSM, jet grouting, and stone columns—are necessary for supporting heavy structures over soft or organic soils.

A structured selection framework based on geotechnical properties, project requirements, and sustainability considerations is essential for effective implementation. Hybrid approaches and innovative materials (e.g., fly ash, recycled aggregates) are increasingly integrated into modern ground improvement strategies, offering both technical and environmental benefits.

Continued research and field validation are vital to refine design guidelines, assess long-term performance, and promote sustainable use of ground improvement technologies in complex geotechnical environments.

7. References

1. Abdel-Rahman MM (2021) Review of Soil Improvement Techniques. In: Shehata H, Badr M (eds) *Advancements in Geotechnical Engineering*. Springer International Publishing, Cham, pp 175–199
2. Alam P, Bawa S (2025) Sustainable Use of Waste Materials in Stone Columns: A Review. *Indian Geotech J* 55:1279–1300. doi: 10.1007/s40098-024-00985-8
3. Al-Arafat M, Enamul Kabir M, Morshed ASM (2024) Geotechnical Challenges in Urban Expansion: Addressing Soft Soil, Groundwater, and Subsurface Infrastructure Risks in Mega Cities. doi: 10.2139/ssrn.5113780
4. Alhamdi MK, Albusoda BS (2021) A Review on Deep mixing method for soil improvement. *IOP Conf Ser: Mater Sci Eng* 1105:012110. doi: 10.1088/1757-899X/1105/1/012110
5. Ali LH, Atemimi YK (2024) Effective Use of Pozzolanic Materials for Stabilizing Expansive Soils: A Review. *IOP Conf Ser: Earth Environ Sci* 1374:012014. doi: 10.1088/1755-1315/1374/1/012014
6. Alimohammadi H, Amirmojahedi M, Tahat JN (2023) A Case History of Application of Deep Compaction Method with Comparison to Different Ground Improvement Techniques. *Transp Infrastruct Geotech* 10:543–568. doi: 10.1007/s40515-022-00229-3
7. Almeida M, Marques M, Riccio M, Fagundes D, Lima B, Polido U, Cirone A, Hosseinpour I (2022) Ground improvement techniques applied to very soft clays: state of knowledge and recent advances. *S&R* 46:e2023008222. doi: 10.28927/SR.2023.008222
8. Alnunu MZ, Nalbantoglu Z (2019) Performance of loose sand with different waste materials in stone columns in North Cyprus. *Environmental Geotechnics* 8:318–323. doi: 10.1680/jenge.18.00079
9. Alqaisi R, Le TM, Khabbaz H (2020) Applications of Recycled Sustainable Materials and By-Products in Soil Stabilization. In: Ameen H, Jamiolkowski M, Manassero M, Shehata H (eds) *Recent Thoughts in Geoenvironmental Engineering*. Springer International Publishing, Cham, pp 91–117
10. Alqawasmeh HM (2025) Enhancing the sustainability of geotechnical engineering with utilization of fly Ash. *Discov Mater* 5:11. doi: 10.1007/s43939-025-00183-0
11. Andavan S, Pagadala VK (2020) A study on soil stabilization by addition of fly ash and lime. *Materials Today: Proceedings* 22:1125–1129. doi: 10.1016/j.matpr.2019.11.323
12. Anderson D, Sburlati D (2016) Monitoring ground-borne and structure-borne noise for management of construction impacts. Brisbane, Australia, pp 1–8



13. Armstrong J, Helm P, Preston J, Loveridge F (2024) Economics of geotechnical asset deterioration, maintenance and renewal. *Transportation Geotechnics* 45:101185. doi: 10.1016/j.trgeo.2024.101185
14. Arpajirakul S, Pungrasmi W, Likitlersuang S (2021) Efficiency of microbially-induced calcite precipitation in natural clays for ground improvement. *Construction and Building Materials* 282:122722. doi: 10.1016/j.conbuildmat.2021.122722
15. Azar SM (2025) Deep Soil Mixing (DSM) with Binders: A State-of-the-Art Method in Ground Improvement Techniques. In: *Advancements in Underground Infrastructures*, CRC Press. CRC Press, pp 1–28
16. Batey T (2009) Soil compaction and soil management – a review. *Soil Use and Management* 25:335–345. doi: 10.1111/j.1475-2743.2009.00236.x
17. Blower T, Preene M (2025) Chapter 3 Problems caused by groundwater. Geological Society, London, *Engineering Geology Special Publications* 31:egsp31-2024–63. doi: 10.1144/egsp31-2024-63
18. Brandi H (1998) Foundation strengthening and soil improvement for scour-dangered river bridges. In: *Geotechnical Hazards*. CRC Press, pp 1–28
19. Chatrabhuj, Meshram K (2024) Use of geosynthetic materials as soil reinforcement: an alternative eco-friendly construction material. *Discov Civ Eng* 1:41. doi: 10.1007/s44290-024-00050-6
20. Chompoorat T, Thepumong T, Khamplod A, Likitlersuang S (2022) Improving mechanical properties and shrinkage cracking characteristics of soft clay in deep soil mixing. *Construction and Building Materials* 316:125858. doi: 10.1016/j.conbuildmat.2021.125858
21. Das BM, Sivakugan N (2018) *Principles of Foundation Engineering*. Cengage Learning, Boston, MA, USA
22. Divya J, Bikku MP, Durga MM, Srujana MV (2022) *Techniques of Ground Improvement and Its Applications*. 12
23. Fillion M-H, Hadjigeorgiou J (2017) Quantifying the Impact of Additional Laboratory Tests on the Quality of a Geomechanical Model. *Rock Mech Rock Eng* 50:1097–1121. doi: 10.1007/s00603-016-1160-4
24. Firoozi AA, Guney Olgun C, Firoozi AA, Baghini MS (2017) Fundamentals of soil stabilization. *Geo-Engineering* 8:26. doi: 10.1186/s40703-017-0064-9
25. Geotechnical Engineering at Soil Mechanics Laboratory Department of Civil Engineering, Faculty of Engineering, Universitas Riau, Indonesia, Nugroho S, Wardani S, Diponegoro University, Engineering Faculty, Department of Civil Engineering, Semarang, Indonesia, Muntohar A, Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Jl. Brawijaya Tamantirto, Bantul, D.I. Yogyakarta, 55183, Indonesia (2023) Density, load and fly ash effect on stabilization of high plasticity soil with lime. *QJES* 16:102–107. doi: 10.30772/qjes.v16i2.925
26. Giroud JP, Han J, Tutumluer E, Dobie MJD (2023) The use of geosynthetics in roads. *Geosynthetics International* 30:47–80. doi: 10.1680/jgein.21.00046
27. Głuchowski A, Miturski M, Rzepczyńska L, Zając K, Sas W (2023) Geopolymerization as a stabilization method for low plasticity clayey silts. *Danube Geotechnical Conference*, Bukarest, Romania, pp 1–9
28. Głuchowski A, Miturski M, Sas W (2019) The Friction and Dilatancy Angle of Recycled Concrete Aggregate. *IOP Conf Ser: Mater Sci Eng* 471:042023. doi: 10.1088/1757-899X/471/4/042023
29. Głuchowski A, Šadzevičius R, Skominas R, Sas W (2021) Compacted Anthropogenic Materials as Backfill for Buried Pipes. *Materials* 14:717. doi: 10.3390/ma14040717
30. Głuchowski A, Sas W (2020) Impact of Cyclic Loading on Shakedown in Cohesive Soils—Simple Hysteresis Loop Model. *Applied Sciences* 10:2029. doi: 10.3390/app10062029
31. Głuchowski A, Sas W (2020) Long-Term Cyclic Loading Impact on the Creep Deformation Mechanism in Cohesive Materials. *Materials* 13:3907. doi: 10.3390/ma13173907
32. Głuchowski A, Sas W, Dzieciół J, Soból E, Szymański A (2018) Permeability and Leaching Properties of Recycled Concrete Aggregate as an Emerging Material in Civil Engineering. *Applied Sciences* 9:81. doi: 10.3390/app9010081
33. Głuchowski A, Soból E, Szymański A, Sas W (2019) Undrained Pore Pressure Development on Cohesive Soil in Triaxial Cyclic Loading. *Applied Sciences* 9:3821. doi: 10.3390/app9183821



34. Gluchowski A, Zając K, Sas W (2023) Evaluating the Long-Term Plastic Strain Accumulation in Reclaimed Asphalt Pavement (RAP) Application for Road Subbase Construction: A Cyclic Triaxial Loading Study. *IOP Conf Ser: Mater Sci Eng* 1297:012013. doi: 10.1088/1757-899X/1297/1/012013
35. Gupta S, Kumar S (2023) A state-of-the-art review of the deep soil mixing technique for ground improvement. *Innov Infrastruct Solut* 8:129. doi: 10.1007/s41062-023-01098-6
36. Gupta S, Kumar S (2023) A state-of-the-art review of the deep soil mixing technique for ground improvement. *Innov Infrastruct Solut* 8:129. doi: 10.1007/s41062-023-01098-6
37. Hessouh JJMM, Eslami J, Beaucour A-L, Noumowe A, Mathieu F, Gotteland P (2023) Physical and mechanical characterization of deep soil mixing (DSM) materials: Laboratory vs construction site. *Construction and Building Materials* 368:130436. doi: 10.1016/j.conbuildmat.2023.130436
38. Ibrahim N, Fayed AL, Ahmed AA, Hammad MS (2022) Effect of vertical drains and preloading on the creep behavior of soft clay. *Innov Infrastruct Solut* 7:203. doi: 10.1007/s41062-022-00780-5
39. Inazumi S, Shakya S (2024) A Comprehensive Review of Sustainable Assessment and Innovation in Jet Grouting Technologies. *Sustainability* 16:4113. doi: 10.3390/su16104113
40. Izadifar M, Luo N, Abu-Farsakh MY, Chen S (2023) Performance Evaluation of Design Methods for Geosynthetic-Reinforced Pile-Supported Embankments. *Transportation Research Record* 2677:458–475. doi: 10.1177/03611981231165994
41. Jia M, Cheng J, Liu B, Ma G (2021) Model tests of the influence of ground water level on dynamic compaction. *Bull Eng Geol Environ* 80:3065–3078. doi: 10.1007/s10064-021-02110-y
42. de Jos D A State-of-the-art Review of Compaction Control Tests Methods
43. Khanday SA, Hussain M, Das AK (2021) A Review on Chemical Stabilization of Peat. *Geotech Geol Eng* 39:5429–5443. doi: 10.1007/s10706-021-01857-1
44. Kumar S, Singh SK (2023) Subgrade soil stabilization using geosynthetics: A critical review. *Materials Today: Proceedings*. doi: 10.1016/j.matpr.2023.04.266
45. Kurda R, Silvestre JD, Brito J de (2018) Toxicity and environmental and economic performance of fly ash and recycled concrete aggregates use in concrete: A review. *Heliyon* 4. doi: 10.1016/j.heliyon.2018.e00611
46. Lei H, Feng S (2024) Vacuum preloading techniques for development and innovation of strengthening dredged soft ground: A review. *Marine Georesources & Geotechnology* 1–20. doi: 10.1080/1064119X.2024.2437692
47. de Lillis A, Fasano G, Flora A, Miliziano S (2022) A novel application of vacuum preloading: conception, analysis and performance evaluation. *Proceedings of the Institution of Civil Engineers - Ground Improvement* 176:121–136. doi: 10.1680/jgrim.21.00058
48. Lu J, Elgamal A, Yan L, Law KH, Conte JP (2011) Large-Scale Numerical Modeling in Geotechnical Earthquake Engineering. *International Journal of Geomechanics* 11:490–503. doi: 10.1061/(ASCE)GM.1943-5622.0000042
49. Madhyannapu RS, Puppala AJ, Bhadriraju V, Nazarian S (2012) Deep Soil Mixing (DSM) Treatment of Expansive Soils. 130–139. doi: 10.1061/41025(338)14
50. Malik P, Mishra SK (2023) A comprehensive review of soil strength improvement using geosynthetics. *Materials Today: Proceedings*. doi: 10.1016/j.matpr.2023.05.710
51. Markiewicz A, Koda E, Kawalec J (2022) Geosynthetics for Filtration and Stabilisation: A Review. *Polymers* 14:5492. doi: 10.3390/polym14245492
52. Miturski M, Dzięcioł J, Szlachetka O (2025) Effect of Dispersed Polypropylene Fibers on the Strength and Stiffness of Cement-Stabilized Clayey Sand. *Sustainability* 17:5803. doi: 10.3390/su17135803
53. Miturski M, Gluchowski A, Sas W (2021) Influence of Dispersed Reinforcement on Mechanical Properties of Stabilized Soil. *Materials* 14:5982. doi: 10.3390/ma14205982
54. Mutman U, Kavak A Improvement of granular soils by low pressure grouting
55. Nagaraju TV, Ravindran G (2025) *Ground Improvement Techniques for Sustainable Engineering*, 1st ed. Bentham Science Publishers, Singapore



56. National Cooperative Highway Research Program, Transportation Research Board, National Academies of Sciences, Engineering, and Medicine (2009) Recommended Practice for Stabilization of Subgrade Soils and Base Materials. Transportation Research Board, Washington, D.C.
57. Njock PGA, Chen J, Modoni G, Arulrajah A, Kim Y-H (2018) A review of jet grouting practice and development. *Arab J Geosci* 11:459. doi: 10.1007/s12517-018-3809-7
58. Petrillo A, Fraternali F, Acampora A, Di Chiara G, Colangelo F, Farina I (2025) Innovative Solidification and Stabilization Techniques Using Industrial By-Products for Soil Remediation. *Applied Sciences* 15:4002. doi: 10.3390/app15074002
59. Pistol J, Kopf F, Adam D, Kummerer C (2024) Deep Vibrocompaction at the Natural Frequency of the Soil Response. *Journal of Geotechnical and Geoenvironmental Engineering* 150:04024076. doi: 10.1061/JGGEFK.GTENG-12351
60. Radziemska M, Gusiati ZM, Holatko J, Hammerschmiedt T, Głuchowski A, Mizerski A, Jaskulska I, Baltazar T, Kintl A, Jaskulski D, Brtnicky M (2021) Nano Zero Valent Iron (nZVI) as an Amendment for Phytostabilization of Highly Multi-PTE Contaminated Soil. *Materials* 14:2559. doi: 10.3390/ma14102559
61. Rodrigues P, Silvestre JD, Flores-Colen I, Viegas CA, Ahmed HH, Kurda R, de Brito J (2020) Evaluation of the Ecotoxicological Potential of Fly Ash and Recycled Concrete Aggregates Use in Concrete. *Applied Sciences* 10:351. doi: 10.3390/app10010351
62. Ruzibiza P (2024) Analysis of Impacts of Geotechnical Investigation on Performance of Construction Projects in Rwanda. Thesis, JKUAT-SABS
63. Safdar MU, Mavroulidou M, Gunn MJ, Garelick J, Payne I, Purchase D (2020) Innovative methods of ground improvement for railway embankment peat fens foundation soil. *Geotechnique* 71:985–998. doi: 10.1680/jgeot.19.SiP.030
64. Safdar MU, Mavroulidou M, Gunn MJ, Purchase D, Gray C, Payne I, Garelick J (2022) Towards the Development of Sustainable Ground Improvement Techniques—Biocementation Study of an Organic Soil. *CircEconSust* 2:1589–1614. doi: 10.1007/s43615-021-00071-8
65. Sas W, Dzięcioł J, Głuchowski A (2019) Estimation of Recycled Concrete Aggregate's Water Permeability Coefficient as Earth Construction Material with the Application of an Analytical Method. *Materials* 12:2920. doi: 10.3390/ma12182920
66. Sas W, Dzięcioł J, Radzevičius A, Radziemska M, Dapkienė M, Šadzevičius R, Skominas R, Głuchowski A (2021) Geotechnical and Environmental Assessment of Blast Furnace Slag for Engineering Applications. *Materials* 14:6029. doi: 10.3390/ma14206029
67. Sas W, Głuchowski A, Alojzy Szymański (2014) CYCLIC BEHAVIOR OF RECYCLED CONCRETE AGGREGATE IMPROVED WITH LIME AND GYPSUM ADDITION. doi: 10.13140/2.1.3441.1202
68. Sas W, Głuchowski A, Gabryś K, Soból E, Szymański A (2016) Deformation Behavior of Recycled Concrete Aggregate during Cyclic and Dynamic Loading Laboratory Tests. *Materials* 9:780. doi: 10.3390/ma9090780
69. Sas W, Głuchowski A, Gabryś K, Soból E, Szymański A (2017) Resilient Modulus Characterization of Compacted Cohesive Subgrade Soil. *Applied Sciences* 7:370. doi: 10.3390/app7040370
70. Sas W, Głuchowski A, Sobol E, Kulkowska M (2015) Experimental studies on crushing of recycled concrete aggregates. *Acta Scientiarum Polonorum Architectura* 14:29–41
71. Schweiger HF, Fabris C, Ausweger G, Hauser L (2019) Examples of successful numerical modelling of complex geotechnical problems. *Innov Infrastruct Solut* 4:2. doi: 10.1007/s41062-018-0189-5
72. Shukla BK, Gupta A, Gowda S, Srivastav Y (2023) Constructing a greener future: A comprehensive review on the sustainable use of fly ash in the construction industry and beyond. *Materials Today: Proceedings* 93:257–264. doi: 10.1016/j.matpr.2023.07.179
73. Skels P, Rozitis J, Ivanovskis N, Kurtiss K (2021) Dynamic compaction of the Baltic basin silty Sand - quality assurance with CPT, DPM, DMT and PLT. *IOP Conf Ser: Earth Environ Sci* 710:012004. doi: 10.1088/1755-1315/710/1/012004
74. Slocombe BC, Bell AL, Baez JI (2000) The densification of granular soils using vibro methods. *Géotechnique* 50:715–725. doi: 10.1680/geot.2000.50.6.715



75. de Souza Junior TF, Heineck KS, Ruver CA, Mohseni APV, da Lopes LS (2023) Application of Dynamic Replacement to Lateritic Clay. *Geotech Geol Eng* 41:4845–4864. doi: 10.1007/s10706-023-02531-4
76. Turan C, Javadi AA, Vinai R, Beig Zali R (2022) Geotechnical Characteristics of Fine-Grained Soils Stabilized with Fly Ash, a Review. *Sustainability* 14:16710. doi: 10.3390/su142416710
77. Verma H, Ray A, Rai R, Gupta T, Mehta N (2021) Ground improvement using chemical methods: A review. *Heliyon* 7. doi: 10.1016/j.heliyon.2021.e07678
78. Vlček J, Gago F, Mihálik J, Malík F, Bahleda F, Prokop J, Štefánik M (2024) Investigation of dynamic effect of rapid impact compaction. *Sci Rep* 14:21364. doi: 10.1038/s41598-024-72728-x
79. Wang S, Lei X-W, Meng Q-S, Xu J-L, Xie L-F, Li Y-J (2020) Influence of Particle Shape on the Density and Compressive Performance of Calcareous Sand. *KSCSE J Civ Eng* 24:49–62. doi: 10.1007/s12205-020-0145-8
80. Wong BYF, Wong KS, Phang IRK (2019) A review on geopolymerisation in soil stabilization. *IOP Conf Ser: Mater Sci Eng* 495:012070. doi: 10.1088/1757-899X/495/1/012070
81. Wu J, Ouyang C, Dai M, Gao Z, Fu H, Wang J (2023) Effect of surcharge loading rate on the performance of surcharge–vacuum preloading with prefabricated horizontal drains. *Marine Georesources & Geotechnology* 41:806–814. doi: 10.1080/1064119X.2022.2101964
82. Zhang J, Jenck O, Dias D (2022) 3D Numerical Analysis of a Single Footing on Soft Soil Reinforced by Rigid Inclusions. *International Journal of Geomechanics* 22:04022113. doi: 10.1061/(ASCE)GM.1943-5622.0002412
83. Zhang Q, An Z, Huangfu Z, Li Q (2022) A Review on Roller Compaction Quality Control and Assurance Methods for Earthwork in Five Application Scenarios. *Materials* 15:2610. doi: 10.3390/ma15072610
84. Characterisation and Mechanical Behaviour of Reconstituted and Stabilised South East Queensland Soft Soils. <https://research-repository.griffith.edu.au/items/6b30f23f-ce1f-42f8-bfdd-5f6227a78d4c>. Accessed 8 Aug 2025