

Sustainability in Geotechnics

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The development of humans and societies has posed huge challenges to geotechnics. Since the adoption of the Sustainable Development Goals established in the United Nations Agenda 2030, adopted in 2015 [1], it has become imperative to seek sustainable solutions that respect the environment and contribute to the mitigation of climate change at an affordable cost, without compromising the safety and stability of geotechnical structures. Indeed, geotechnics is currently undergoing a transformative shift towards sustainability. Embracing sustainable practices in geotechnics involves integrating new and smart materials, nature- and bio-based materials and technologies, the use of nanotechnology and artificial intelligence, advances in constitutive soil models by integration of climate effects, and holistic design approaches that consider environmental, economic, and social implications throughout the life cycle assessment of geotechnical structures.

The Special Issue “Sustainability in Geotechnics” was launched with an invitation to authors from all over the world to address current and future sustainable solutions in geotechnics. Twenty-five manuscripts were submitted to this Special Issue, and sixteen were accepted for publication. Contributions were received from nine countries (Brazil, China, Japan, Norway, Poland, Portugal, Saudi Arabia, Slovakia, and the United Kingdom), representing three continents (America, Asia, and Europe); these papers address some of the emerging topics, focusing on the research, design, construction, and performance of sustainable geotechnical works.

The first three contributions deal with the recovery of mining tailings in geotechnics. Coelho and Camacho (Contribution 1) characterize iron ore tailings from a geotechnical perspective, studying their physical and identification (grain size and plasticity) properties, compaction behavior, and stress–strain properties under monotonic and cyclic triaxial undrained loading. The study highlights some particularly important characteristics of iron ore tailings such as a significant silty component that is responsible for the low plasticity observed, particles with an angular shape, their very high solid density, and their higher angle of friction and liquefaction resistance than common granular geomaterials. The results indicate that there is a high potential for mining tailings to be used in a wide variety of geotechnical applications. One such example is presented by Saldanha et al. (Contribution 2), where the potential use of iron ore tailings for replacing the conventional aggregates used in interlocking paving blocks for lightly trafficked pavements is explored. The study focuses not only on mechanical performance (in terms of compressive strength), but also on environmental performance through a life cycle assessment (cradle-to-gate), demonstrating the clear advantages of valorizing mining tailings. Correia et al. (Contribution 3) study sustainable ways of increasing the stability of mining tailing deposits, which is a current concern given the large number and size of such deposits. To this end, they propose the use of bio-stabilization techniques, combining the use of biopolymers (xanthan gum and carboxymethyl cellulose) with bioremediation (bio-stimulation and bioaugmentation). The results show that both polymers applied alone (albeit in low concentrations—1%) are effective sustainable stabilizers and an alternative to



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Portland cement. Bioaugmentation was revealed to be an ineffective technique, while biostimulation combined with xanthan gum showed very good results in terms of unconfined compressive strength. Moreover, the study revealed that bio-based techniques, such as soil engineering techniques, are promising, offering environmentally friendly alternatives for sustainable soil stabilization and contributing to a greener and more sustainable future.

The fourth, fifth, sixth, and seventh contributions study sustainable ways of improving the mechanical behavior of different soils. The fourth and fifth contributions propose the use of bio-inspired techniques (enzymes and biopolymers) to replace the use of cement in soil stabilization, while the sixth contribution proposes a sustainable solution by partially replacing Portland cement with industrial by-products and/or biochars; the seventh contribution proposes the potential use of coarse aggregate crushing waste to improve the geotechnical properties of a silty sand soil. Mwandira et al. (Contribution 4) propose an innovative method that uses hybrid enzyme carriers (copper-carbonic anhydrase) to catalyze the bioprecipitation of calcium carbonate, aiming to increase the efficiency and sustainability of the biocementation process. Venda Oliveira and Reis (Contribution 5) study the effects of soil's organic matter content on the biostabilization induced by the biopolymer xanthan gum. The results showed a detrimental effect in terms of unconfined compressive strength and stiffness, as well as an increase in compressibility and primary consolidation time for organic matter contents higher than 5.5%. Hov et al. (Contribution 6) study viable alternatives (four biochars, including demolition wood and sewage waste, and five industrial by-products, including ashes and slags) as a partial replacement of Portland cement for the stabilization of three soils (a soft clay, a quick clay, and one peat). The results suggest that the stabilization effect of Portland cement combined with biochars increases with the increasing water content of the soils, while the opposite effect was observed for Portland cement combined with industrial by-products. Further studies should be carried out to establish the correlations between the mineralogical and chemical composition of these additives, as well as the mechanical performance of the stabilized soils. Abdullah et al. (Contribution 7) investigate the reusing of coarse aggregate crushing waste mixed with Portland cement to improve the geotechnical properties of soil when applied in road construction. It was found that a combination of 10% coarse aggregate crushing waste with 2% Portland cement increases the undrained shear strength, the California Bearing Ratio (CBR), and the P-wave velocity, making such a soil improvement approach almost carbon neutral.

Soares et al. (Contribution 8) propose a framework to assess soil liquefaction based on the ratio between the shear wave velocity and the peak undrained deviatoric stress. The authors state that such a ratio can be accurately used to define a boundary between liquefaction and strain hardening for sands and between strain softening and strain hardening for silty sands and silts. This tool has the potential to assess the liquefaction of in situ soils, including natural deposits or mine tailings, contributing to safer and more sustainable geotechnical structures.

The ninth and tenth contributions (Contributions 9 and 10, respectively) study the interaction of soil-sustainable reinforcement elements under monotonic and cyclical loading. The ninth contribution focuses on geogrids, while the tenth contribution focuses on wooden frame beams and bamboo anchor rods. Barajas et al. (Contribution 9) study the pullout apparatus scale (small and large) effect on the characterization of the soil-geogrid interface shear behavior. It was found that the pullout apparatus scale effect is small for confining stresses greater than or equal to 50 kPa, so the adoption of small-scale equipment is less material- and time-consuming, making it a more sustainable way of characterizing such interfaces. Yang et al. (Contribution 10) conducted a series of model tests in embankment slopes supported by wooden frame beams and bamboo anchor rods under train loadings complemented with three-dimensional numerical simulations. The stresses acting on the support/reinforcement elements depend on loading magnitude and frequency, as well as the slope depth. It was shown that this ecological and environmentally friendly support system is not only a sustainable solution, but also contributes to increasing slope stability.

Nguyen et al. (Contribution 11) propose a methodology to deal with uncertainty in the direct shear tests used to characterize the shear parameters of a soil reinforced with polyester fibers. The authors state that it is not recommended to carry out direct shear tests with only three specimens since different combinations of three specimens provide different shear strength parameters. Therefore, it is important to evaluate the uncertainty of the shear strength parameters by taking into account all the test procedures and material variability.

Wu et al. (Contribution 12) present a novel technique for constructing the protection and seepage control layer in Cemented Sand, Gravel and Rock (CSGR) dams. The advantages of this new method, integrated with dam body construction, were demonstrated in a case study, showing significant economic, environmental, and safety benefits, thus promoting sustainable dam construction.

Tinoco et al. (Contribution 13) use machine learning techniques, namely artificial neural networks and genetic algorithms combined with modern optimization processes, aiming to develop a slope classification system for rock and soil cuttings, as well as embankments based on visual features that are usually collected during routine inspection. This slope stability assessment tool can allow railway infrastructure management companies to collect less information to determine the stability level of their slope network (reducing costs without compromising safety issues), allowing for the strategic investment of the available budget on critical slopes. This approach is an important contribution to the efficient and sustainable management of geotechnical transportation infrastructures.

The last three contributions present case studies demonstrating the application of sustainability concepts in geotechnics. Pedro et al. (Contribution 14) postulate that one of the best solutions for improving sustainability in the construction sector is to improve the design and construction methods, thereby reducing material consumption. Such a strategy was applied to a real case of shaft construction, where it was demonstrated that optimizing the characteristics of the lining of the shaft can result in a reduction in CO₂ emissions by at least 50% without compromising the safety engineering requirements. Takahashi et al. (Contribution 15) investigate the long-term durability of cement-treated soil on an artificial island of Central Japan International Airport, where the pneumatic flow mixing method was first fully introduced; this method uses dredged soil rather than soil transported from cuttings, and uses small amounts of Portland cement, allowing it to be classified as a sustainable ground improvement method. The results showed negligible deterioration 20 years after construction, demonstrating that there is no need for energy or materials for repair, i.e., the cement-treated soil offers many environmental and economic benefits, and consequently increases sustainability. Kitazume (Contribution 16) presents the recent case histories of carbon-neutral activity using ground improvement technology in Japan. Some ways to reduce material consumption, with environmental, social, and economic benefits, can be implemented by promoting the recovery of industrial waste and by-products, as well as the development of new materials with negative emission technology such as biomass materials.

The integration of sustainable solutions in geotechnics is not merely a trend but a necessity for building a resilient and environmentally responsible future. By leveraging new and smart materials, nature- and bio-based materials and technologies, nanotechnology, artificial intelligence, advanced soil models, and life cycle assessment, geotechnical engineers can design and implement projects that meet the current and future demands of modern society while safeguarding our planet. As the scientific community continues to innovate and adopt these sustainable practices, the field of geotechnics will play a key role in shaping a sustainable and resilient built environment.

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List of Contributions

1. Coelho, P.; Camacho, D. The Experimental Characterization of Iron Ore Tailings from a Geotechnical Perspective. *Appl. Sci.* **2024**, *14*, 5033. <https://doi.org/10.3390/app14125033>.
2. Saldanha, R.B.; Menezes, M.F.L.; Bittar, R.J.; Consoli, N.C. Performance of Ore Sand as Aggregate for Interlocking Blocks. *Appl. Sci.* **2023**, *14*, 48. <https://doi.org/10.3390/app14010048>.
3. Correia, A.A.S.; Caldeira, J.B.; Branco, R.; Morais, P.V. Enhancing the Strength of Mine Residue Soil by Bioremediation Combined with Biopolymers. *Appl. Sci.* **2023**, *13*, 10550. <https://doi.org/10.3390/app131810550>.
4. Mwandira, W.; Purchase, D.; Mavroulidou, M.; Gunn, M.J. Synthesis and Utilisation of Hybrid Metal-Carbonic Anhydrase Enzyme Carrier System for Soil Biocementation. *Appl. Sci.* **2023**, *13*, 9494. <https://doi.org/10.3390/app13179494>.
5. Oliveira, P.J.V.; Reis, M.J.F.C.C. Effect of the Organic Matter Content on the Mechanical Properties of Soils Stabilized with Xanthan Gum. *Appl. Sci.* **2023**, *13*, 4787. <https://doi.org/10.3390/app13084787>.
6. Hov, S.; Paniagua, P.; Sætre, C.; Long, M.; Cornelissen, G.; Ritter, S. Stabilisation of Soft Clay, Quick Clay and Peat by Industrial By-Products and Biochars. *Appl. Sci.* **2023**, *13*, 9048. <https://doi.org/10.3390/app13169048>.
7. Abdullah, G.M.S.; El Aal, A.A.; Al Saiari, M.; Radwan, A.E. Sustainable Impact of Coarse Aggregate Crushing Waste (CACW) in Decreasing Carbon Footprint and Enhancing Geotechnical Properties of Silty Sand Soil. *Appl. Sci.* **2023**, *13*, 10930. <https://doi.org/10.3390/app131910930>.
8. Soares, M.; da Fonseca, A.V.; Ferreira, C.; Rios, S. Static Liquefaction Assessment Combining Shear Wave Velocity, Peak Strength and Soil Grading. *Appl. Sci.* **2023**, *13*, 8580. <https://doi.org/10.3390/app13158580>.
9. Barajas, S.R.; Pedroso, G.O.M.; Ferreira, F.B.; da Silva, J.L. Influence of Apparatus Scale on Geogrid Monotonic and Cyclic/Post-Cyclic Pullout Behavior in Cohesive Soils. *Appl. Sci.* **2024**, *14*, 5861. <https://doi.org/10.3390/app14135861>.
10. Yang, H.; Huang, G.; Wei, Z.; Jiang, X.; Cao, Z. A Study on the Dynamic Response of a Timber-Frame Beam-Bamboo Anchor-Supported Roadbed Slope under Train Load. *Appl. Sci.* **2024**, *14*, 2426. <https://doi.org/10.3390/app14062426>.
11. Nguyen, G.; Masarovičová, S.; Gago, F.; Grzybowska-Pietras, J. Application of Direct Shear Test to Analysis of the Rate of Soil Improvement with Polyester Fibres. *Appl. Sci.* **2024**, *14*, 4601. <https://doi.org/10.3390/app14114601>.
12. Wu, Y.; Jia, J.; Zheng, C.; Jia, B.; Wang, Y.; Baah, W.A. A New Method for Constructing the Protection and Seepage Control Layer for CSGR Dam and Its Application. *Appl. Sci.* **2024**, *14*, 5423. <https://doi.org/10.3390/app14135423>.
13. Tinoco, J.; Correia, A.G.; Cortez, P.; Toll, D. An Evolutionary Neural Network Approach for Slopes Stability Assessment. *Appl. Sci.* **2023**, *13*, 8084. <https://doi.org/10.3390/app13148084>.
14. Pedro, A.M.G.; Repsold, L.; e Sousa, J.A. Assessing the Sustainability of Alternative Shaft Construction Methods. *Appl. Sci.* **2024**, *14*, 4476. <https://doi.org/10.3390/app14114476>.
15. Takahashi, H.; Sato, I.; Morikawa, Y.; Ozawa, A. Long-Term Durability of Cement-Treated Soil Used in Offshore Airport Island Construction. *Appl. Sci.* **2023**, *13*, 8081. <https://doi.org/10.3390/app13148081>.
16. Kitazume, M. Recent Case Histories of Carbon-Neutral Activity Using Ground Improvement Technology in Japan. *Appl. Sci.* **2023**, *13*, 8985. <https://doi.org/10.3390/app13158985>.

Reference

1. UN-A/RES/70/1; Transforming Our World: The 2030 Agenda for Sustainable Development, in Resolution Adopted by the General Assembly on 25 September 2015. United Nations: New York, NY, USA, 2015.

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