The integration of environmental considerations into Geotechnical Engineering Education: Balancing optimization and sustainability

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ABSTRACT: Balancing technical performance with environmental sustainability is becoming a central challenge in geotechnical engineering. Traditional design methods often assume negligible displacements, leading to overly conservative and resource-intensive solutions. In contrast, accepting moderate displacements—when compatible with structural performance—can enable more economical and sustainable designs. This paper explores how such optimization strategies can be integrated into geotechnical engineering education. Techniques including rigid inclusions, soil reinforcement, and performance-based design are presented as means to reduce material consumption without compromising stability. Numerical modelling and project-based learning are emphasized as essential tools for teaching these trade-offs. Real-world case studies illustrate how students can assess structural performance, quantify environmental impact, and develop holistic design approaches. The paper underscores the importance of embedding environmental considerations into geotechnical curricula to prepare engineers capable of delivering resilient, cost-effective, and sustainability-driven infrastructure.

Keywords: Sustainability, Optimization, Settlement, Reinforcement, Modelling

1 Introduction

As sustainability becomes a global priority, geotechnical engineers are increasingly tasked with delivering infrastructure that is both resilient and environmentally responsible. This challenge extends to education, where future engineers must be equipped not only with technical expertise but also with an understanding of environmental trade-offs.

Traditional design approaches often rely on conservative assumptions, such as zero settlement, leading to overdesigned and resource-intensive solutions. In contrast, performance-based methods that allow controlled settlements—when structurally acceptable—enable more sustainable outcomes. Techniques like reinforced soil systems and rigid inclusions can reduce dependence on deep foundations, cutting material use and environmental impact.

To embed these principles in education, numerical modelling and project-based learning are essential. They allow students to explore soil–structure interaction under varied conditions and assess the trade-offs between performance, cost, and sustainability. These experiences foster innovation and prepare graduates to develop efficient, environmentally conscious geotechnical solutions (Kibert, 2008).

2 Integrating environmental considerations into geotechnical decision-making

Geotechnical engineering has traditionally focused on technical performance and cost efficiency. However, growing environmental concerns now demand a more holistic approach that balances structural stability, economic viability, and sustainability (Basu et al., 2014). This shift requires rethinking established practices and embedding environmental considerations into each phase of design and construction.

Conventional solutions often rely on deep foundations and rigid safety assumptions that, while structurally conservative, result in excessive material use and a high carbon footprint. Performance-based design enables engineers to accept controlled settlements within safe limits, reducing overdesign. Sustainable alternatives such as rigid inclusions, ground improvement, and geosynthetic reinforcement optimize resource use while maintaining stability. Contemporary geotechnical practice incorporates sustainability through strategic material choices, bioengineering, and flexible structural systems.

Recent studies such as Ottaviani et al. (2024) have emphasized the growing role of carbon calculators in quantifying environmental impact, especially in the design of geosynthetic-based solutions. Educating future geotechnical engineers requires integrating sustainability across the curriculum. Numerical modelling, quantified case studies, and design-performance assessments foster a deep understanding of environmental trade-offs. Project-based learning allows students to engage with real-world constraints and evaluate multiple design paths based on technical and ecological performance.

3 Optimized solutions: Balancing technical efficiency with environmental sustainability

A sustainable approach requires balancing technical efficiency, cost-effectiveness, and ecological responsibility. One key shift involves accepting controlled settlements and adopting alternative reinforcement methods, which can significantly reduce resource consumption while maintaining structural integrity. This section presents optimized geotechnical solutions that achieve this balance, with real-world case studies illustrating their successful application.

3.1 Principles of sustainable geotechnical design

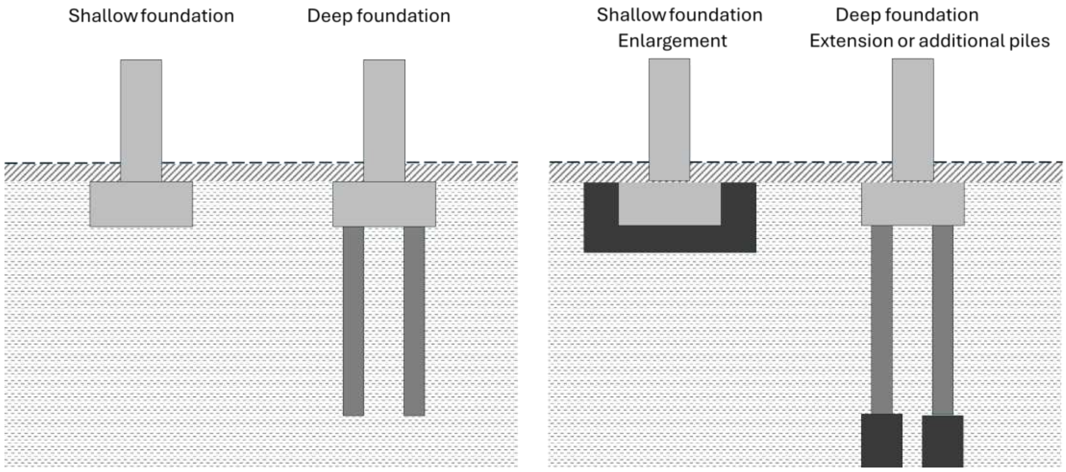
To integrate sustainability into geotechnical engineering, optimized solutions must adhere to key design principles:

- Resource Efficiency: Minimize material usage by optimizing foundation design, limiting excavation, and reusing existing soil where possible.
- Performance-Based Design: Allow for moderate settlements within safe limits to reduce reliance on deep foundations and heavy reinforcement.
- Soil Reinforcement & Ground Improvement: Implement techniques such as rigid inclusions, geosynthetics, and ground stabilization to enhance soil performance while reducing environmental impact.
- Minimizing Environmental Disruption: Prioritize construction methods that reduce soil disturbance, groundwater contamination, and carbon emissions.

The following sections analyse specific geotechnical solutions that embody these principles.

3.1.1 Case Study 1: Rehabilitation of historic buildings and foundation reinforcement

Reinforcing historic building foundations presents the dual challenge of ensuring structural stability while preserving architectural integrity. Traditional replacement methods are invasive, resource-intensive, and often unsustainable. In contrast, targeted reinforcement techniques—such as micropiles and high-pressure grouting—can redistribute loads and enhance bearing capacity with minimal excavation (Leung et al., 2011). As shown in Figure 1, these methods offer a more sustainable alternative, improving load performance while reducing material use and environmental disruption.



a) Existing foundations of historic building **b) Sustainable improvement of foundations**

Figure 1. Reinforcement techniques for enhancing load-bearing capacity

These reinforcement strategies optimize resource efficiency, reduce carbon emissions, and limit construction waste. Moreover, geotechnical modelling and real-time monitoring enable engineers to refine reinforcement strategies, ensuring long-term structural stability while minimizing environmental impact (Misra & Basu, 2011).

Example: Rehabilitation of Historic Structures and Foundation Reinforcement – The Macdonald Warehouse Project, Paris

This case study presents the transformation of the Macdonald warehouse complex in Paris (originally built in the 1970s) into a mixed-use facility including residential units, offices, and public services. The building's dimensions (600 x 60 meters) and its founding conditions—on approximately 500 piles embedded in Saint-Ouen limestone overlying Beauchamp sands—posed significant geotechnical and structural challenges. To meet the demands of the planned superstructure extensions, a hybrid foundation reinforcement strategy was adopted.

Following a thorough diagnostic campaign, it was determined that approximately 75% of the existing piles could be reused if their load-bearing capacity was enhanced. High-pressure jet grouting was selected as the primary technique for reinforcing the pile tips. Columns with a diameter of 1.3 meters and a length of 3 meters were installed directly through the existing piles using rotary drilling and high-pressure cementitious injection. In addition to jet grouting, 2,700 new micropiles, each 8 meters long, were installed to support the new vertical structural elements such as elevator shafts and stairwells.

These micropiles served both to redistribute loads and to mitigate settlement risks in areas subject to differential loading. Field load tests on both individual and grouped micropiles validated the design assumptions and ensured compatibility with the existing foundation system. The cross-sectional layout of the Macdonald warehouse project, as shown in Figure 2, presents the combined use of jet-grouting columns and new micropiles within the site's geological stratigraphy. This configuration illustrates how hybrid foundation solutions can be effectively adapted to complex ground conditions while preserving existing infrastructure.

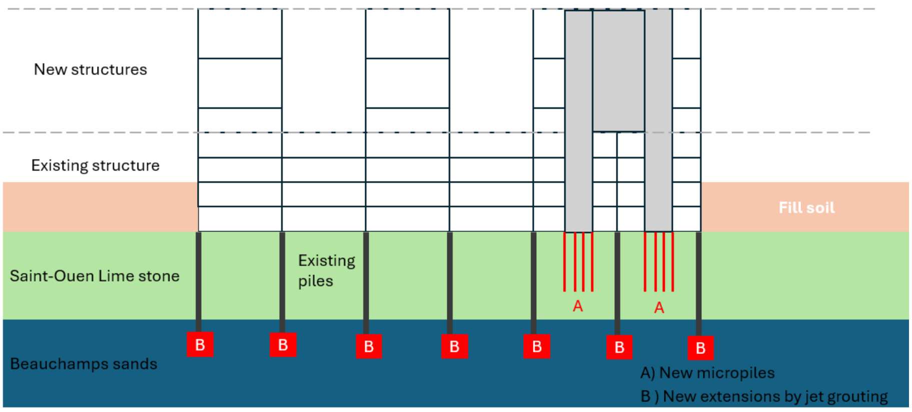


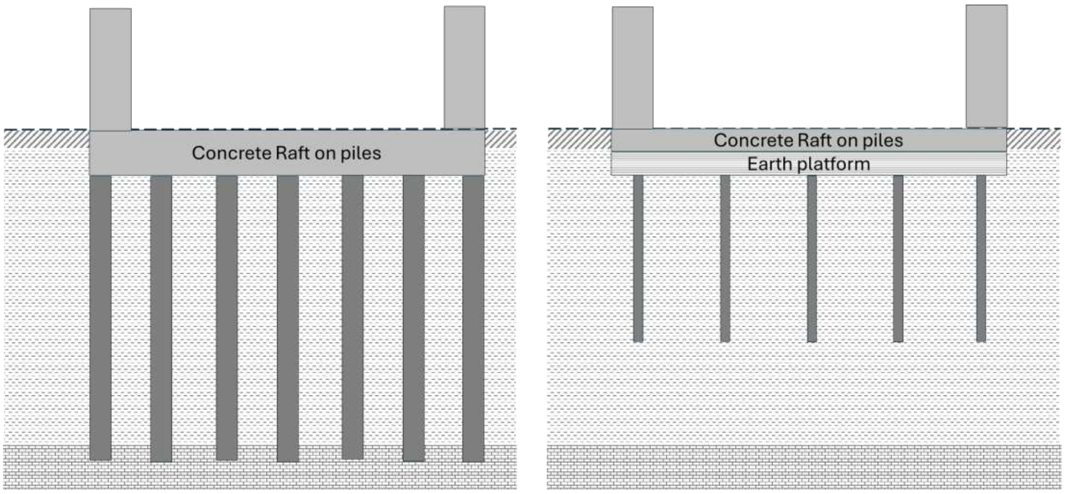
Figure 2. Cross-sectional diagram of the Macdonald foundation system showing jet-grouting columns, new micropiles, and geological stratigraphy.

This project exemplifies how targeted foundation reinforcement—through a combination of reuse, high-pressure grouting, and micropile implementation—can ensure long-term structural performance with minimal environmental disruption. By limiting demolition, excavation, and material waste, the Macdonald warehouse rehabilitation also contributes to broader sustainability goals. This project was conducted during the author's time at Terrasol, where our team was responsible for the geotechnical diagnosis and foundation reinforcement design for the transformation of the Macdonald Warehouse into a mixed-use development.

3.1.2 Case Study 2: Settlement-tolerant foundation systems with soil improvement

The design of industrial foundations—such as for tanks, reservoirs, and wind turbines—often targets strict settlement limits. Traditional deep foundations minimize differential settlement but at high material and environmental cost. Where moderate settlements are tolerable, soil improvement methods offer more sustainable alternatives (Okyay et al., 2012).

Rigid inclusions, such as controlled modulus or grouted stone columns, enhance soil capacity and optimize load transfer (Okyay et al., 2010). Preloading and geosynthetic reinforcement further reduce post-construction settlement and distribute loads efficiently. As shown in Figure 3, these strategies reduce material use and environmental impact while preserving structural performance.



a) Traditional deep foundation **b) Sustainable alternative with rigid piles**

Figure 3. Comparison between a traditional deep foundation and a sustainable alternative

By integrating these soil improvement strategies, engineers can reduce reliance on deep foundations while maintaining structural performance. This approach lowers carbon emissions by decreasing concrete and steel usage and minimizes excavation-related environmental impacts. Furthermore, optimizing foundation design to tolerate moderate settlements within safe limits reduces construction costs and leads to more resource-efficient geotechnical solutions.

Example: Sustainable Foundation Design for a Water Treatment Plant in Pont-Audemer, France

A full-scale geotechnical study was carried out to evaluate the performance of rigid inclusions as a soil reinforcement technique beneath a large-diameter concrete water tank at the Pont-Audemer water treatment facility in northern France. The site was characterized by deep, compressible soft soils underlying a superficial fill layer, posing significant challenges in terms of settlement control and structural stability. Conventional deep foundation solutions were deemed economically and environmentally inefficient for this context. Instead, a more sustainable alternative was implemented: the foundation system employed rigid inclusions with a diameter of 28 cm, installed in a 3 m × 3 m grid, extending through the soft soil strata. To facilitate effective load distribution and settlement control, a cement-stabilized earth-platform was constructed above the inclusions. This platform served as a critical load transfer medium, allowing vertical stresses from the tank structure to be partially distributed across both the inclusions and the surrounding soil. The design promoted a composite behaviour that enhanced bearing capacity while limiting differential settlement. Figure 4 provides both the plan and final views of the water treatment tank constructed in Pont-Audemer, France.

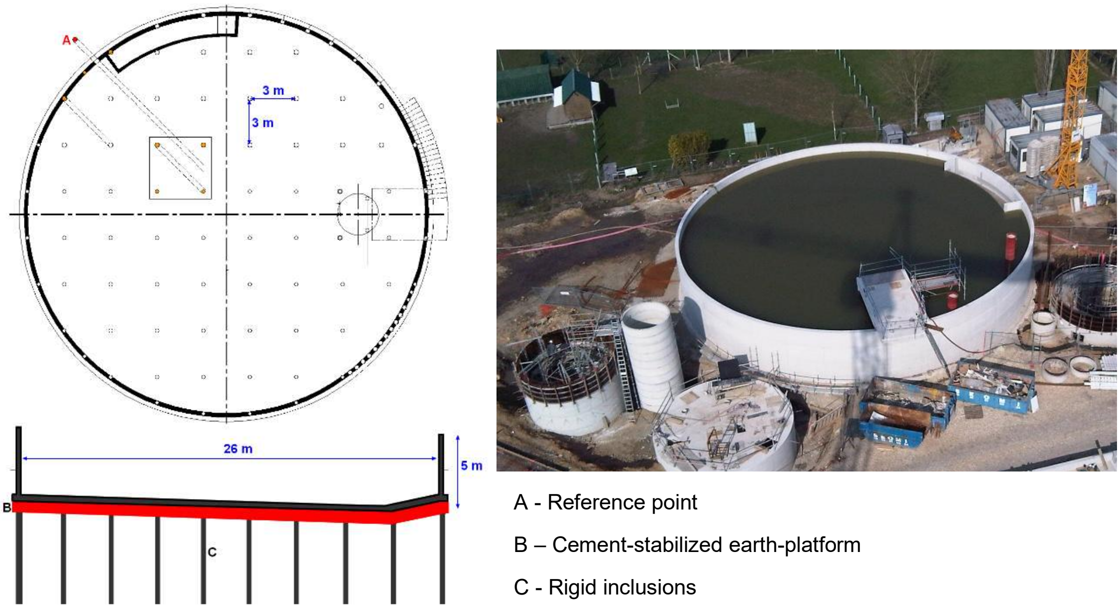


Figure 4. Plan and final views of the structure (from PINTO)

The site was extensively instrumented with settlement sensors and earth pressure cells strategically placed beneath both the centre and perimeter of the tank. These instruments enabled continuous monitoring of vertical displacements and stress distribution throughout the construction and operational phases. The collected field data were further analysed and validated through advanced three-dimensional numerical modelling using Ansys, which accurately simulated the soil–structure interaction under cyclic loading conditions. The monitoring results revealed that the maximum settlement at the tank centre was limited to 17 mm, remaining well within the design serviceability threshold of 20 mm (Figure 5). This demonstrated the system's ability to effectively control differential settlements and confirmed the reliability of the inclusion-based reinforcement strategy under realistic loading scenarios.

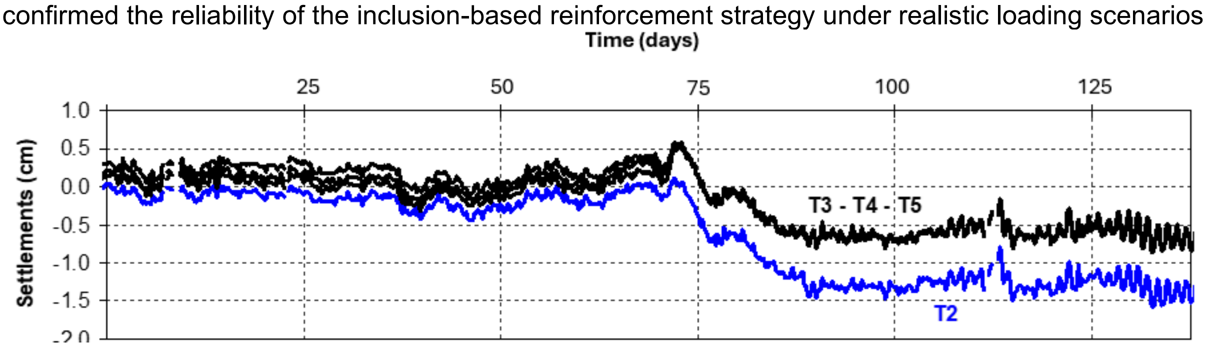


Figure 5. Settlement under the centre of the water concrete tank

Field measurements also indicated that vertical stresses at the heads of the rigid inclusions consistently ranged between 1500 and 1600 kPa, confirming efficient stress transfer from the structure to the reinforced soil system (Figure 6). This stress concentration demonstrated the effectiveness of the inclusions in mobilizing load-bearing capacity while minimizing stress propagation to the surrounding compressible soil.

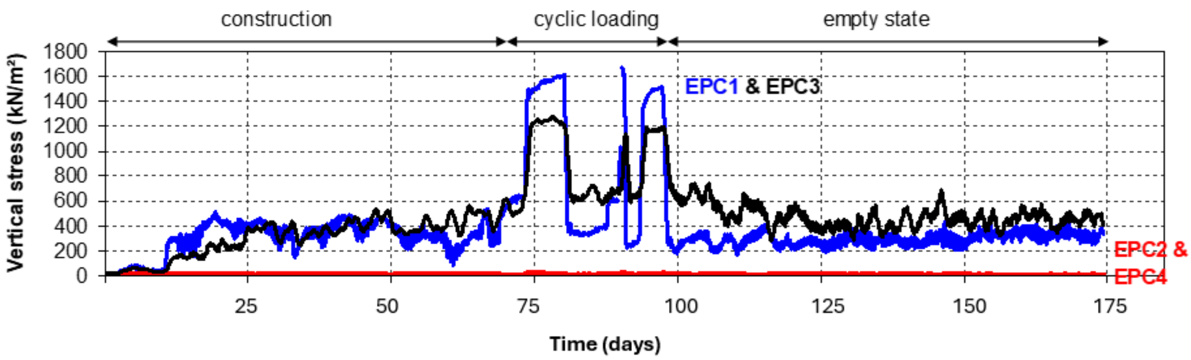
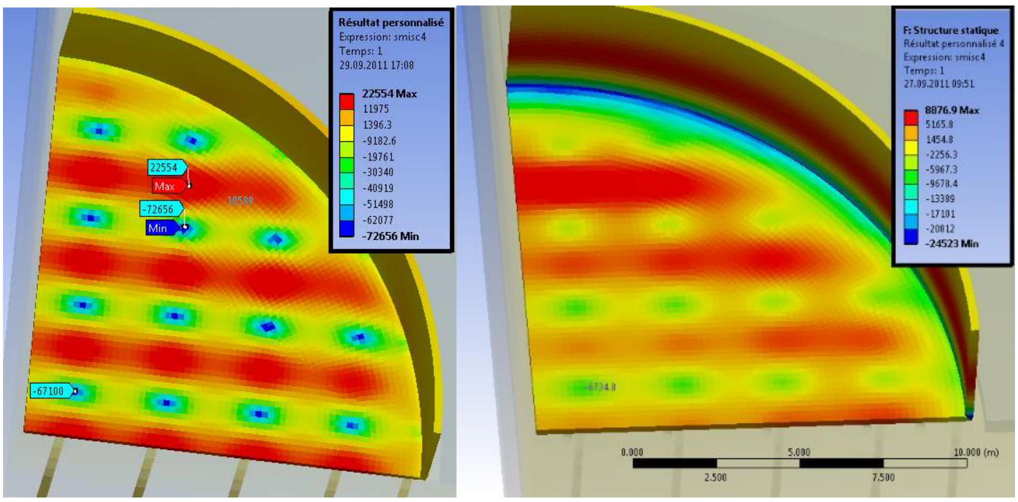


Figure 6. Stress distribution at inclusion head and soil

Long-term monitoring under repeated cyclic loading conditions confirmed the stabilization of settlements over time, with no observable degradation in structural performance or loss of load transfer efficiency. This demonstrated the durability and resilience of the rigid inclusion system under service loading scenarios representative of operational conditions for water storage infrastructure. Further structural analysis revealed a significant reduction in bending moments within the raft foundation when rigid inclusions were used in place of conventional piles. Figure 7 illustrates the bending moment distributions on raft foundations using two different reinforcement strategies—piles and rigid inclusions. The comparison demonstrates how the use of rigid inclusions significantly reduces internal forces, resulting in a more efficient and sustainable structural response. Numerical simulations showed that, with piles, the maximum negative moment at support was −72.6 kN·m, and the maximum positive moment in span was +22.6 kN·m. In contrast, when rigid inclusions were employed, the maximum negative moment at support was reduced to −6.7 kN·m, and the maximum positive moment in span decreased to +8.9 kN·m. This substantial reduction in internal forces indicates that rigid inclusions significantly alleviate structural demand on the raft, contributing to a more economical and durable foundation design.



a) Bending moments on raft with piles **b) Bending moments on raft with rigid inclusions**

Figure 7. Reinforcement techniques for enhancing load-bearing capacity

Replacing deep piles with rigid inclusions at Pont-Audemer yielded a 35% reduction in concrete use and over 25% lower CO_2 emissions, while minimizing excavation and spoil transport. This approach significantly reduced the project's environmental footprint.

Educationally, the case offers rich material for performance-based learning. Students can analyse real monitoring data, simulate soil–structure interaction using FEM tools, and compare traditional and optimized designs. Tools like the IGS Carbon Calculator enable environmental impact quantification, helping students balance performance and sustainability in design decisions. This project was carried out during the author's time at PINTO, where I was involved in the geotechnical design and monitoring of the rigid inclusion system beneath a large water storage tank at the Pont-Audemer treatment facility.

3.1.3 Flexible retaining structures as an alternative to rigid concrete walls

Retaining structures are vital for slope stabilization and soil retention in geotechnical design. Traditional concrete walls provide strength but require deep foundations, extensive materials, and drainage systems. They are also vulnerable to cracking under settlement or seismic loads.

As shown in Figure 8, flexible retaining systems—such as MSE walls, gabions, and soil-nailed walls—offer sustainable alternatives. These systems use geosynthetics and natural drainage to reduce material use and adapt to ground movement. MSE walls reinforce backfill with geogrids, allowing controlled deformation and reducing excavation. Gabions offer permeable, low-cost solutions ideal for riverbanks and erosion control. Soil-nailed systems, combining steel bars and geosynthetic facings, are particularly effective in confined urban excavations (Elias & Juran, 1991). These solutions reduce environmental impact, improve adaptability, and support sustainable design in diverse contexts.

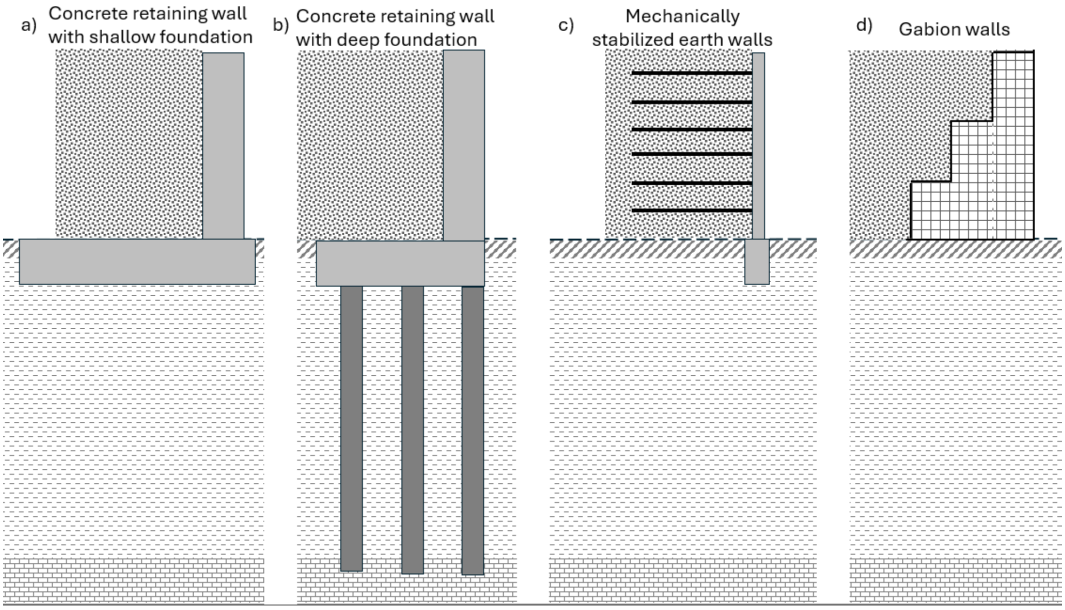
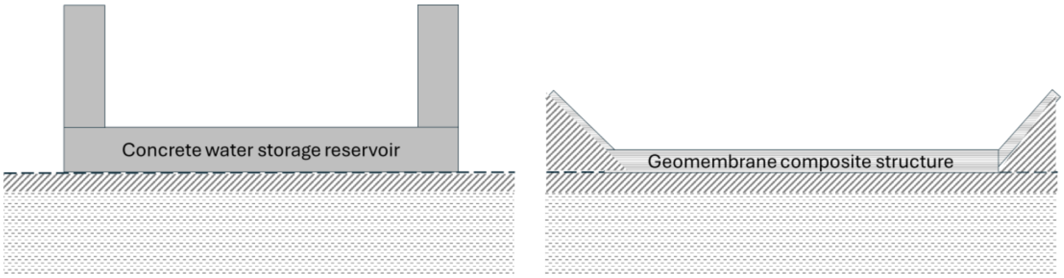


Figure 8. Comparison of retaining walls: rigid vs. flexible solutions

Compared to traditional concrete walls, flexible retaining structures require fewer raw materials, are more adaptable to settlements, and have a lower carbon footprint. Their ability to integrate with natural landscapes and improve long-term performance makes them a preferred choice for sustainable geotechnical solutions.

3.1.4 Case Study 4: Water storage basins – Large raft foundations vs. Geomembranes

The design of water storage basins is critical in geotechnical engineering, requiring impermeability, structural durability, and stability in various ground conditions. Traditionally, reinforced concrete slabs have been used as foundation systems for basins, providing a rigid and watertight base. While effective, these structures demand high material consumption, extensive excavation, and significant carbon emissions due to the use of concrete and steel. Additionally, in compressible or weak soils, differential settlement can cause cracking and loss of structural integrity, leading to costly repairs and water leakage (Han et al., 2020). A sustainable and adaptable alternative is the use of geomembrane-lined basins, which employ synthetic liners. These flexible membranes create a quasi-impermeable barrier that prevents seepage while conforming to ground deformations, reducing the risk of settlement-induced failure. Compared to rigid concrete slabs, geomembranes require minimal excavation, eliminate the need for deep foundations, and significantly lower material costs. Figure 9 contrasts a classical concrete foundation system with a sustainable alternative incorporating geomembranes. This comparison underscores how geosynthetic solutions can achieve comparable performance while significantly reducing the carbon footprint and material demand of foundation systems.



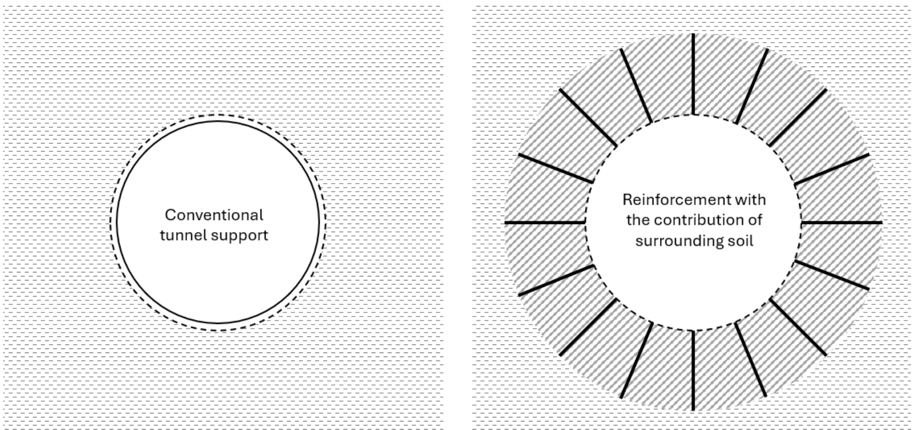
a) Concrete structure with classical design b) Geomembrane-lined basin as a sustainable alternative

Figure 9. Comparison of (a) a rigid concrete foundation and (b) a sustainable geosynthetic solution for water storage.

Geomembrane-lined basins also offer superior chemical resistance and durability, making them ideal for industrial wastewater storage, irrigation reservoirs, and landfill liners. Unlike concrete, which can degrade over time due to chemical exposure, geomembranes maintain their integrity under harsh environmental conditions, extending service life and reducing maintenance costs. A key advantage of geosynthetic drainage layers is their ability to enhance stability by reducing uplift pressures and preventing liner displacement. Compared to traditional concrete slabs, geomembrane liners offer a lower-carbon, cost-effective, and more resilient solution for water storage applications. Their ability to adapt to varying soil conditions, resist cracking, and reduce material consumption makes them a preferred choice in sustainable geotechnical engineering.

3.1.5 Case Study 5: The new Austrian tunnelling method (NATM) versus conventional tunnel support systems

Tunnelling is one of the most complex challenges in geotechnical engineering, particularly in soft or weak ground conditions, where maintaining stability while minimizing material use is a key concern. Conventional tunnelling methods typically rely on rigid support systems, such as precast segmental lining, steel ribs, or immediate application of thick shotcrete layers. These techniques are based on the assumption that tunnel linings must fully bear the surrounding ground load, often leading to over-conservative designs, excessive reinforcement, and increased project costs. In contrast, the New Austrian tunnelling Method (NATM) takes a fundamentally different approach by utilizing controlled ground deformations to redistribute stresses, allowing the surrounding soil or rock to actively contribute to tunnel stability (Figure 10). This method enables a more flexible and resource-efficient tunnelling process, making it a preferred choice for sustainable infrastructure projects (Jenny et al., 1987).



a) Concentional tunnel support b) Sustainable alternative with NATM Method

Figure 10. Comparison of conventional tunnel retaining methods and reinforced soil techniques

In comparison to traditional tunnelling techniques, NATM significantly improves material efficiency, excavation control, and adaptability to varying geological conditions. Conventional tunnelling often relies on full-face excavation with pre-determined thick linings, leading to excessive material use and higher project costs. NATM, on the other hand, integrates sequential excavation with progressive support adjustments, leading to cost savings and improved safety margins. The ability to incorporate controlled deformations ensures that the surrounding rock mass plays an active role in supporting the tunnel, reducing the demand on structural reinforcements.

By allowing engineers to make real-time adjustments based on observed site conditions, NATM aligns with modern performance-based design principles, ensuring that tunnel construction is not only structurally sound but also resource-efficient. The reduced reliance on rigid pre-designed supports makes it particularly well-suited for projects where sustainability and material conservation are priorities. As geotechnical engineering moves toward more sustainable construction practices, the principles of NATM serve as a model for integrating adaptive design, real-time monitoring, and optimized material use in underground infrastructure development.

3.1.6 Case Study 6: Optimizing geotechnical design through the observational method

Geotechnical design often faces uncertainty due to variable soil and rock conditions. Traditional approaches rely on high safety factors, leading to overdesign, excess material use, and higher costs. The observational method (Peck, 1969) offers a more adaptive strategy: designs are based on expected conditions with contingency plans that adjust in real time as site data evolves. Instrumentation—such as inclinometers, piezometers, and settlement gauges—guides these adjustments, enabling targeted reinforcement only where needed and reducing environmental impact (Okyay et al., 2012). A practical application was during the EOLE project in Paris, where compensation grouting stabilized existing buildings during tunnel excavation by offsetting settlements in real time (Figure 11). This method exemplifies sustainable, performance-based design under urban constraints.

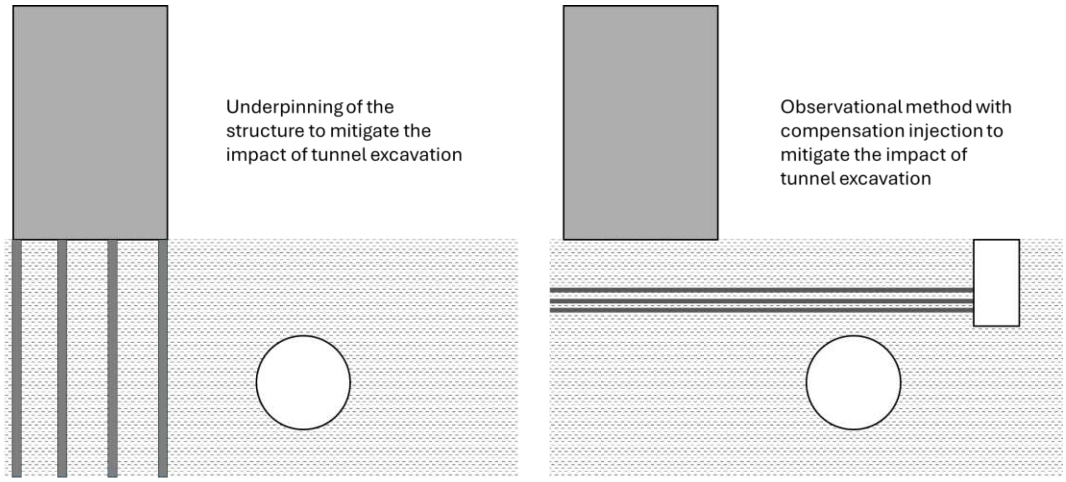


Figure 11. Example of the observational method with settlement compensation

Widely used in excavations, tunnelling, and slope stabilization, the observational method is especially effective in urban settings to minimize settlements and protect adjacent structures. By enabling performance-based adjustments, it reduces material use and supports sustainability.

While it requires skilled teams and robust monitoring, its successful implementation enhances adaptability, lowers costs, and significantly cuts the environmental footprint of geotechnical projects.

4 Concluding remarks

The future of geotechnical engineering lies in its ability to respond to global sustainability challenges through innovation, efficiency, and environmental responsibility. As infrastructure demands grow and climate constraints intensify, engineers must be equipped not only with technical competence but also with the mindset to develop resource-conscious solutions that minimise impact without compromising safety or performance.

This paper has demonstrated that sustainable geotechnical design is not an abstract concept but a practical reality—achievable through performance-based methods, smart material use, and integrated environmental assessment. Case studies presented here illustrate how technologies such as rigid inclusions, geosynthetics, geomembranes, and observational design can significantly reduce carbon footprints, construction waste, and material consumption.

To prepare future engineers for this paradigm, geotechnical education must evolve. Curricula should emphasise:

- Analytical tools for quantifying environmental impact (e.g. carbon calculators),
- Simulation-based learning for design trade-offs,
- Case-driven teaching grounded in real projects, and
- Interdisciplinary collaboration to understand broader system interactions.

Embedding sustainability into geotechnical education ensures that graduates are not only capable designers but also critical thinkers who can balance performance, cost, and environmental goals in a rapidly changing world. This transformation is essential if geotechnical engineers are to lead the profession in delivering infrastructure that is resilient, responsible, and future-ready.

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Dr. Umur Salih OKYAY is a Civil Engineer with a Ph.D. in Geotechnical Engineering and a certified professional geologist. With extensive experience in structural engineering and complex infrastructure projects, he has contributed to the design, analysis, and supervision of major civil engineering works, including bridges, underground structures, high-rise buildings, hydraulic infrastructures, and deep excavations. Throughout his career, he has worked closely with both public and private institutions, providing innovative solutions to complex engineering challenges.

Beyond his professional engagements, Dr. OKYAY has a deep passion for education and knowledge dissemination. He has been actively involved in higher education for over a decade, teaching in various engineering schools and universities. His courses cover key topics such as soil and rock mechanics, ground improvement, geotechnical structures, and sustainable engineering solutions. He integrates real-world case studies into his teaching, offering students a practical perspective on the challenges and advancements in geotechnical engineering.

Dr. OKYAY has published multiple research articles in international journals and has presented his work at numerous national and international conferences. He is an active member of several prestigious organizations, including the French Committee for Soil Mechanics, the International Society for Soil Mechanics and Geotechnical Engineering.

Through his teaching and research, Dr. OKYAY aims to bridge the gap between academia and industry, ensuring that future engineers acquire the necessary skills to address the evolving challenges of geotechnical engineering and infrastructure resilience. His dedication to education and mentoring contributes significantly to the development of the next generation of civil engineers.