Review Article

Future Trends in Ground Improvement: A Review

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This paper examines the dynamic terrain of ground improvement, with a specific emphasis on forthcoming trends that hold the potential to revolutionise the discipline. This study explores various aspects of construction practices that have been influenced by technological advancements, environmental considerations, and the need for sustainability. These areas of focus include sustainable techniques, use of advanced materials, application of geotechnical robotics, data analytics, strategies for climate resilience, integration of renewable energy, risk mitigation, sustainable earthworks, interdisciplinary education, and international collaboration. This review offers significant insights into developing trends in ground improvement, thus providing a roadmap for the future of the construction industry. It envisions a construction sector that is more efficient, resilient, and sustainable.

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1. Introduction

The construction sector, a continuous catalyst for innovation, has continually adjusted to the changing demands of society, used advancements in technology [1], and prioritised environmental sustainability [2][3] as a fundamental priority. In the midst of the always-changing realm of building practises, the field of ground improvement arises as a vital profession that forms the foundation on which our built environment flourishes. This study undertakes a captivating exploration, emphasising the importance of investigating ground improvement, both in its present condition and in the perspective of upcoming developments that are expected to revolutionise this important topic.

The range of factors that have an impact on ground improvement is extensive and significant [4]. These factors include technological advancements that redefine our abilities, environmental concerns that require environmentally conscious solutions, and a pressing need for sustainability that prompts us to reassess traditional approaches. The study explores several aspects of construction practises that are closely interconnected, as we examine the emerging trends that have the potential to bring about significant changes in the future.

The scope of this study covers a wide range of topics, all of which have great importance for the future of ground improvement. The aforementioned topics include Sustainable Ground Improvement Techniques, Advanced Material Science, Geotechnical Robotics, Advanced Monitoring and Data Analytics, Climate Resilience, Integration of Renewable Energy, Risk Assessment and Mitigation, Sustainable Earthworks, Education and Workforce Development, and International Collaboration. Through a comprehensive review of these factors, we are able to reveal the significant influence of ground improvement on the sustainability, resilience, and flexibility of the construction sector in light of forthcoming problems.

2. Sustainable Ground Improvement Techniques

2.1. Eco-Friendly Additives

The growing worldwide emphasis on sustainability has fuelled research in ground improvement technologies, with an emphasis on environmentally friendly additives in both chemical stabilisation and grouting [5]. To reduce environmental effects, the trend is towards biodegradable and non-toxic materials [6].

In Nigeria, where infrastructure development is vital, Julius Berger's Abuja Kaduna road project stands out for its revolutionary cold recycling process. This technology reuses milled-off pavement material to create a road's bitumen-stabilized base course layer. This method provides: a) increased road carrying capacity, prolonging its lifetime and decreasing future maintenance requirements; and b) reduced mining operations and disposal of old asphalt, helping the environment by saving resources and minimising habitat damage and emissions.

Furthermore, this technique reduces construction traffic, reducing congestion, air pollution, and interruptions to local populations.

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2.2. Sustainability Assessment

The pursuit of sustainability is increasingly prioritising the use of life cycle evaluations and sustainability measures. In forthcoming studies, there will be a heightened emphasis on measuring the impact of both the environmental and economic advantages associated with sustainable ground development strategies, as highlighted by Raymond et al., (2021)[7]. The sector is poised to undergo a significant transformation as a result of the increasing emphasis on sustainability-driven decision-making.

3. Advanced Material Science

3.1. Nanomaterials

The integration of nanomaterials into ground improvement practices is a burgeoning area of interest. Nanosilica, nanoparticles, and nanotubes hold the potential to significantly enhance soil properties and durability [8]. The relentless exploration of these materials is anticipated to revolutionize the field.

3.2. Smart Materials

The field of smart materials that possess the ability to self-monitor and react to dynamic soil conditions is an area of growing interest and has considerable promise [9]. These materials have the potential to deliver real-time feedback and allow for modifications to be made during ground improvement procedures, leading to a period characterised by increased accuracy and efficiency in the field of geotechnical engineering.

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a. For instance, Khudher et al., (2020)[10] reported the use of nanomaterial-enhanced soil stabilization where nanosilica could be incorporated into the soil during compaction processes. This application aims to bolster the load-bearing capacity of the soil, reducing settlement over time and creating a stable foundation, which is particularly valuable in urban construction projects.

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1. Another illustrative instance pertains to the use of self-healing smart geotextiles inside regions distinguished by frequent road construction and repair activities. According to Abedi et al., (2023) [11], the use of smart geotextiles containing self-repairing polymers has the potential to autonomously dispense healing agents when subjected to fractures or damage. This innovative approach has the capability to significantly prolong the lifetime of pavements and enhance the overall durability of road infrastructure.
2. Furthermore, the use of intelligent embankments that are equipped with integrated sensors is a viable approach to address the challenges associated with highway construction [12][13][14]. The sensors would consistently monitor the soil conditions and, when identifying an excess of moisture or settlement, initiate automatic actions such as implementing controlled drainage systems or reinforcing the soil. This is done to ensure the stability and safety of the embankment.

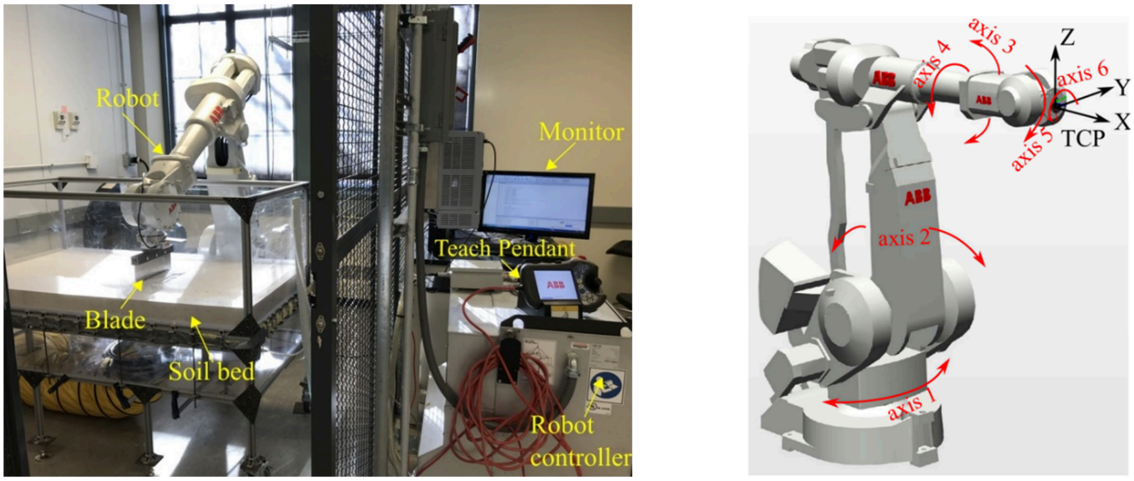
4. Geotechnical Robotics, Advanced Monitoring, and Data Analytics

4.1. Autonomous Machinery

According to Melenbrink et al., (2020)[15], the integration of autonomous robotic machinery holds significant potential for the advancement of ground improvement techniques. This includes the utilisation of autonomous drilling rigs, grouting machines, and drones for site inspection, which are expected to revolutionise the construction industry by improving safety measures and operational efficiency.

The Cross-rail Project in London, UK, serves as an interesting example of the practical use of this technology in real-world contexts. Geotechnical robots made a major contribution to many tasks such as drilling, ground stabilisation, and tunnel inspection, thereby reducing human dangers and enhancing construction efficiency. According to Macchiarulo et al., (2019)[16], sophisticated monitoring systems were used to consistently evaluate ground conditions, thereby guaranteeing the safety and stability of the tunnelling process. This case study highlights the potential for revolutionary advancements in ground improvement through the use of autonomous robots and sophisticated monitoring systems. It provides insight into the prospects of a future characterised by enhanced safety and efficiency.

Figure 1 shows another example of small-scale geotechnical testing carried out with a six-axis robot. It is often used to explore geomechanics problems related to the interactions between soils and other objects, such as structures or machine components.



(a) (b)

Figure 1. Testing facility using robots (a) Key components and (b) Cartesian coordinate system relating to the device: source [17]

4.2. IoT Sensors

The continuous rise of Internet of Things (IoT) sensors for the purpose of collecting real-time data is positioned to revolutionise ground improvement methodologies. According to Payero et al., (2017)[18], these sensors herald a new age of proactive problem-solving.

One illustrative instance of their influence may be seen in a geologically active region such as San Francisco, where a substantial 60-story high-rise building used Internet of Things (IoT) sensors integrated into its foundation and structural elements [16]. The sensors provided constant monitoring of ground motions, soil density, and structural stresses, hence presenting the following benefits:

- The implementation of early earthquake alert systems that have been shown to be crucial in mitigating potential harm and safeguarding the well-being of those present in affected areas. These diligent sensors have demonstrated their efficacy by promptly detecting seismic activity and issuing timely warnings, minimising the likelihood of injuries and assuring the safety of both inhabitants and pedestrians.
- Real-time changes for enhanced efficiency were made possible by the use of sensors, via providing real-time insights into ground conditions and structural loads. This enabled construction modifications to be made on the fly, resulting in improved efficiency.

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- The use of continuous monitoring and early problem identification has significantly enhanced the long-term stability of the skyscraper, hence reducing the frequency of maintenance requirements.

4.3. Machine Learning

Machine learning algorithms are taking a progressively significant part in the field of ground improvement. According to Munoz Perez et al., (2023)[19], the use of predictive modelling and risk assessment in design has the potential to significantly enhance accuracy and efficiency, leading to a revolutionary impact.

5. Climate Resilience and Integration of Renewable Energy

5.1. Climate-Adaptive Ground Improvement

Given the problems posed by climate change, there is a growing need for the development and enhancement of ground improvement methods in order to strengthen the resilience of soil. The focus of research endeavours is aimed at addressing the consequences of escalating sea levels [20], augmented precipitation, and severe weather occurrences on building projects [21].

The use of ground improvement methods that are adaptable to climate conditions plays a vital role in ensuring the stability and resilience of infrastructure. An example can be seen in Miami Beach, Florida, where a comprehensive initiative integrating elevated roadways, seawalls, and beach replenishment has effectively mitigated the occurrence of floods, thus safeguarding both valuable assets and the tourist industry [22][23].

5.2. Geothermal Ground Improvement

The integration of ground improvement techniques with geothermal energy systems has great potential. The technique described in this study employs fundamental features to facilitate energy exchange, hence mitigating energy consumption and promoting sustainability [24][25].

6. Sustainable Earthworks, Risk Assessment, and Mitigation

6.1. Green Infrastructure

The integration of ground improvement techniques is increasingly being recognised as a valuable component of green infrastructure initiatives, with a particular emphasis on urban green spaces [1]. The integration of these practices serves to improve soil quality and facilitate the provision of ecosystem services, hence promoting the alignment of building practices with principles of environmental stewardship.

The "Greening of Durban" initiative in South Africa is widely regarded as a notable and exemplary instance. Durban encountered a range of urban predicaments resulting from fast urbanisation, including floods, soil degradation, and ecological depletion arising from deforestation and urban expansion [26].

In order to tackle these challenges, Durban has adopted a variety of pioneering green infrastructure technologies. One of the strategies used was the establishment of urban woods, which aimed to improve air quality, mitigate soil erosion, and boost water retention. The city also used several strategies, such as the implementation of green roofs and bioretention zones, to efficiently manage rainfall, thereby mitigating the risks of floods and erosion. Furthermore, regions susceptible to erosion were subjected to the implementation of vegetation controls aimed at safeguarding riverbanks and slopes, contributing to the preservation of water bodies. The establishment of community gardens was undertaken with the objective of enhancing soil quality and facilitating the availability of locally cultivated agricultural products.

The results had a profound impact and brought about significant changes. The enhancement of soil quality, reduction in erosion, and reduced frequency of flooding episodes were observed. The "Greening of Durban" initiative has had a significant impact on the regeneration of biodiversity in the region, hence playing a crucial role in the restoration of local ecosystems.

6.2. Advanced Geohazard Mitigation

Researchers have made significant advancements in the development of novel ground improvement methods aimed at mitigating geohazards, including but not limited to landslides, sinkholes, and coastal erosion [27][28]. Significant emphasis is placed on the advancement of early warning systems in order to strengthen safety measures.

The Italian Alps serve as a notable example, characterised by their susceptibility to landslides as a result of the complex topography and geological conditions. According to Frigerio et al., (2014)[29], the implementation of the sophisticated Landslip Monitoring and Early Warning System has been crucial in preventing human casualties and mitigating property damage.

The system consists of a combination of ground sensors, inclinometers, GPS devices, and rain gauges, carefully installed in locations susceptible to landslides. The transmission of data occurs in real-time to a central station using modern communication technology, enabling prompt analysis. Sophisticated algorithms are used to assess data pertaining to factors such as soil moisture and ground movement in order to identify potential landslip triggers. These algorithms are designed to automatically generate warnings, which are then disseminated to relevant authorities and the general public via a variety of communication channels [30].

In one prominent case, forecasters warned of coming severe rain. The system expeditiously identified increases in soil moisture levels and observed slight ground movements in a vulnerable region. Authorities reacted quickly after issuing evacuation warnings that made it possible for safe evacuations. Although there was infrastructure damage as a result of a second landslip, no injuries were reported.

This particular scenario highlights the actual implementation of sophisticated geohazard mitigation techniques and emphasises the crucial significance of early warning systems in protecting both human lives and infrastructure from the adverse effects of landslides.

7. Education, Workforce Development and International Collaboration

7.1. Interdisciplinary Training

In order to cultivate cooperation and promote innovation, there is an increasing focus on multidisciplinary education for professionals in the field of geotechnical engineering [1]. Effective collaboration with environmental scientists, data analysts, and materials scientists is vital in addressing all the difficulties associated with ground improvement.

The Thames Tideway Tunnel Project in London, UK, serves as an excellent example of multidisciplinary collaboration. The successful management of sewage overflow into the River Thames during periods of severe rainfall is contingent upon the collaboration of a multidisciplinary team.

- Geotechnical and civil engineers maintain tunnel stability.
- Environmental scientists: They protect the river ecology.
- Data Analysts and Modellers: They forecast the behaviour of the ground.
- Safety Specialists: They safeguard the safety of workers and the general public.

The use of an interdisciplinary strategy in the Thames Tideway Tunnel Project has resulted in its transformation into a noteworthy prototype of effective ground improvement. This method encompasses several disciplines such as engineering, environmental conservation, data analysis, and safety protocols. As a result, the project has successfully provided a sustainable resolution to an important urban issue.

7.2. Knowledge Sharing

Global collaboration is pivotal in advancing ground improvement techniques, particularly in regions prone to natural disasters and soil-related challenges. Sharing best practices, research findings, and experiences will accelerate progress and drive innovation worldwide.

8. Conclusion

Finally, this paper provided a comprehensive review of future trends in ground improvement, shedding light on this discipline's revolutionary potential in the construction industry. The following are the key results of this research:

- The construction sector is increasingly embracing sustainable ground improvement techniques as a result of its growing commitment to environmental responsibility. This transition is characterised by the use of eco-friendly additives and the implementation of sustainability evaluations. These methodologies not only optimise project effectiveness but also mitigate environmental consequences and foster long-term sustainability.
- The integration of nanomaterials and smart materials has significant potential in enhancing soil characteristics and longevity within the realm of Advanced Material Science. The aforementioned materials possess the capacity to significantly improve the field of geotechnical engineering, offering enhanced accuracy and effectiveness in the field of ground improvement techniques.
- The future of ground improvement is anticipated to be driven by the integration of autonomous equipment, Internet of Things (IoT) sensors, and machine learning techniques in the fields of

Geotechnical Robotics, Advanced Monitoring, and Data Analytics. These technological advancements contribute to the improvement of safety, efficiency, and design correctness, hence facilitating a paradigm shift towards proactive problem-solving.

- Climate resilience and the integration of renewable energy are becoming more important in the field of ground improvement methods. These techniques are being developed and adapted to effectively tackle the difficulties posed by climate change and to facilitate the incorporation of renewable energy systems. As a result, construction projects are becoming more robust and sustainable in nature.
- Ground improvement is increasingly being included in green infrastructure projects and used as a means of mitigating geohazards, contributing to sustainable earthworks and risk reduction. Efforts are now underway to create early warning systems with the aim of bolstering safety measures and safeguarding communities from the impact of natural disasters.
- Education, workforce development, and international collaboration play crucial roles in the advancement of ground improvement approaches via interdisciplinary training and information exchange. The acceleration of development and stimulation of creativity on a worldwide scale may be facilitated by collaboration with specialists from other sectors and by fostering international cooperation.

These new trends have the potential to enhance the efficiency, resilience, and sustainability of the construction sector. Nevertheless, it is essential to confront the obstacles associated with the adoption of technology, environmental issues, climate adaptation, regulatory frameworks, and international collaboration in order to completely achieve this objective.

9. Recommendations

The following recommendations to the professional body responsible for engineering education are suggested:

- Encourage universities to strengthen their engineering programmes by adding courses that include current trends in infrastructure development.
- Stress the need for interdisciplinary education to prepare engineers for successful cross-disciplinary collaboration.
- Initiatives for Continuous Learning: Create programmes to educate engineers on the newest techniques and technology for improving the ground.

- Facilitate opportunities for hands-on training and research, especially in areas like geotechnical robots and nanomaterials, to develop practical knowledge.

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