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Biogeotechnics: A Review of Challenges, Opportunities and Perspectives in Geotechnical Applications

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ABSTRACT

Biogeotechnics is a relatively new concept in geotechnical engineering that potentially has positive impact on environmental modification as well as improve soil properties. Biogeotechnics uses eco-based technologies such as living organisms and their biproducts to modify the soil properties whilst reducing damage to the environment or ecosystems. The aim of biogeotechnics is to provide active and better solutions involving ground improvement, thereby reducing the environmental impact on geotechnical operations. This can include using plants to enhance slope stability or prevent erosion, using microorganisms to break down pollutants, and using other living organisms to improve soil structure. The results of biogeotechnic projects can include improved soil stability, improved water quality, increased biodiversity, and reduced erosion. This paper presents a review of the fundamentals of biogeotechnics concepts, their challenges, opportunities and perspectives when applied to geotechnical engineering, and underscores its potential role in delivering UN sustainable development goals as well as achieving net zero carbon.

Keywords: Biogeotechnics, Ground improvement, Calcite precipitation, Sustainability, Net-Zero Carbon.

1 INTRODUCTION

Ground improvement and soil treatment are some of the most important geotechnical engineering works that directly interact with various aspect of the environment. Conducting appropriate soil treatment and ground improvement which causes least environmental damage has been established as a goal for environmental geotechnics (Martinez et al., 2022). Although researchers and experts have taken significant steps in the soil improvement aspects, compatibility with the environment is still one of the basic concerns that remains. Hence, implementation of new methods that can reduce the environmental effects of ground improvement are being widely considered (Chittoori et al., 2020). In addition to this compatibility, the possibility of improving the geo-engineering properties of soils has also been the focus of geotechnical engineers (Yue et al., 2020).

Biogeotechnics is an interdisciplinary field which combines the principles of biology, geology, and civil engineering to understand and manage the interactions between living organisms and the natural environment. This field refers to the engineering application of living organisms and their products to improve soil properties and support plant growth; thus providing significant positive impact on environmental protection whilst delivering sustainable projects (e.g. embedding low carbon). This can include using microorganisms to break down organic matter, using mycorrhizal fungi to improve nutrient uptake, and using earthworms to aerate and mix soil (Lai et al., 2021). Biogeotechnics techniques are sometimes used in combination with other soil-improvement methods e.g. adding organic matter or using cover crops to achieve improved soil properties (Gowthaman et al., 2019). Biogeotechnics is an alternative to more traditional soil-improvement techniques and is often used in sustainable ground modifications (Liu et al., 2019). These techniques can be used in a variety of ways to improve soil properties, remoulding soils, protected modification (eco-treatments), and support plant growth e.g. using microorganisms to break down organic matter, which can improve soil structure (Yue et al., 2020). Another example is using microorganism to increase the strength of soil, durability, reducing the void ratio and porosity or reducing pore water pressures; which helps to restore the soil textures (Mitchell, 2020; Lai et al., 2021). Recent studies on biogeotechnics application on soil improvements show great promise. Some techniques utilise soil microbial processes such as microbially induced calcite

precipitation (MICP) to treat subsurface soil characteristics like soil activity, collapsibility, etc. (Umar et al., 2016, Zhang et al., 2023 and Wang et al., 2023). So, understanding the basics of microorganism actions on soil treatment can be useful for future researchers involved in biogeotechnics.

As one of the global sustainability commitments by various governments and authorities to cut greenhouse gases, the authors consider that biogeotechnics could play a critical role in Net Zero strategies and this is echoed by Song et al. (2020). Application of the biogeotechnics technologies helps to replace the traditional geotechnical procedures with new methods that have less impact on ecosystems such as removing grouting, mitigating the ground remoulding from the use of bentonite, by using non-destructive methods instead of destructive soil treatments (Mavroulidou, 2018; Martinez et al., 2022). According to the UN Sustainable Development target goals especially goals 9 and 11 which is aimed to improve *'build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*' and '*make cities and human settlements inclusive, safe, resilient and sustainable'*; the engineering community has a pivotal role to play in delivering the UNSUG20230 (UNDESA, 2023). In this regard, biogeotechnics has a part to play in such global scope, through the use of new technologies that provide environmental friendly solutions as well as geotechnical deliverability. In such cases using techniques that mitigate the results of geotechnical works can change the practical aspect of soil treatments and ground improvement techniques.

2 BACKGROUND

The soil treatments using environmentally compatible methods started long ago e.g. Jacot (1936); although soil improvement itself has a longer history as far back as early 1800. However, environmental-based soil improvement is considered a new technology that has found its place in geotechnical engineering today (Wang et al., 2020). Basically, the main idea of biogeotechnics was developed by using biology and microbiology principles to provide adaptive geotechnical solutions for ground engineering purposes and associated with least environmental impacts (Gomez et al., 2017). The biggest factor in biological activity in the soil is the amount of organic matter/mechanism present which is known as bio-mediated soil improvement systems (Umar et al., 2016). Using this factor to soil improvements is one of the aims in biogeotechnics.

DeJong et al. (2010) mentioned the use of biological processes to improve soil engineering properties as a new opportunity that leads to providing more environmental friendly methods. Calcite precipitation, microbial-/bial- induce, vermi-biowaste, biochar, fertilizers, bacterial treatment, restriction fragment length polymorphism (RFLP), biogrout, and mosses are the main soil improvement techniques which are recommended in biogeotechnics (Achal & Kawasaki, 2016; Ye et al., 2017; Mavroulidou, 2018; Tao et al., 2019; Terzis & Laloui, 2019; Mavroulidou & Shah, 2021; Mavroulidou et al., 2022).

Of course, the soil modification has a considerably deep background in geotechnical engineering; but biogeotechnics is the new term of soil stabilization and improvement with high respect to the environment. Biogeotechnics is the terminology for geoenvironmental biotechnology that involves harnessing various living organisms (e.g., plants, microorganisms, etc.) in construction and engineering projects to improve the overall health and stability of the ecosystems (Gomez et al., 2017; Mavroulidou et al., 2020). It has recently gained attention as a novel, progressive, compatible, eco-friendly, cost-effective, and long-term solution. It is a relatively new aspect of geotechnics which has been gaining popularity in recent times due to its ability to address various environmental issues and improve the sustainability, modification for geotechnical projects.

Biogeotechnics considers alternative environmental-based procedures which aim to stabilize soils, improve soil structure, and remediate pollutants with less damage on ecosystems. This is achieved with plants, microorganisms, and other living organisms that are specially chosen for their ability to thrive in the specific environment where the project is being undertaken.

Biogeotechnical methods and their detailed mechanisms, applications, influencing factors and capabilities over conventional methods are presented by various researchers which indicate special advancements of biogeotechnics regarding engineering and environmental aspects. Whiffin et al. (2007) developed the idea of bioclogging, which is a way to significantly reduce the hydraulic conductivity or permeability of sands. The results showed that the hydraulic conductivity was significantly lower. Ivanov and Chu (2008) used the bioclogging methodology to verify lowering of hydraulic conductivity in granular soils which is considered as proof for previous works.

Ivanov et al. (2010) shows a remarkable reduction in permeability in soils (50% to 99%) after using biotreatment. According to Chang and Cho (2012), the biodegradation of beta-1,3/1,6-glucan polymers result in the formation of fibres that serve as soil reinforcements. Baharuddin et al (2013) used the biological modification to increase the engineering improvements for a grouting project which achieved low carbon emission. Biopolymers have recently been promoted as an environmentally friendly alternative for strengthening sand. Due to their potential for bioclogging, the application of biopolymers was initially limited to contamination immobilization. In addition, their potential as a soil stabilizing agent has been investigated (Burbank et al., 2013).

He & Chu (2014) used microbially induced desaturation and precipitation (MIDP) to monitor the mitigation of liquefaction during earthquakes. Cheng & Cord-Ruwisch (2014) conducted a study and stated that the calcite formation in the voids of soils results in a decrease in porosity, an increase in the resistance to water flow, and the creation of new preferred flow paths for the transmission of cementation fluids. Gomez et al. (2014) stated that the bacteria, which are either urease-producing or denitrifying, make it possible to biostimulate calcite precipitation. Torgal et al (2015) provide a principle understanding about bioencapsulation, biodesaturation, bioplugging, biocementation, and biogrouting methods as alternative for traditional procedures in soil improvements.

Khan et al. (2016) examined the possibility of augmenting native Pararhodobactor sp. with artificial beach rock formations as a means of mitigating coastal erosion at Okinawa, Japan. Chang and Cho (2016) found that 5% gellan gum-treated sand had an unconfined compressive strength of up to 44 MPa. O'Donnell et al. (2017) and Kangda et al (2023) utilized the microbially induced calcite precipitation (MICP) for long-term monitoring and analysis of mitigation of liquefaction and the results showed that the soil geotechnical properties were modified significantly. Bao et al (2017), Jiang and Soga (2017) applied MICP in different soil stabilization which increased the soil strength on some transportation projects.

Pardo et al. (2018) showed that the biochar additives have a minor (negligible) effect on the effective strength of drained sand. Ni et al. (2018) investigated the hydraulic conductivity and gas permeability of biochar-modified soils. The addition of biochar to the soil was interpreted as reducing the gas permeability and saturated hydraulic conductivity. Simatupang et al. (2018) conducted research with the enzyme which showed a significant increase in resistance to liquefaction were more efficient than MICP and MIDP techniques.

Bao et al (2019) focused on application of bio-advancements on liquefaction modifications. Ni et al (2019) investigated water retention characteristics and hydraulic conductivity of lignocellulose fibre-low plasticity silt composites. The outcomes revealed an increase in the soil's liquefaction potential as well as an increase in its porosity and permeability. Gowthaman et al. (2019) used isolated bacteria and MICP on the Hokkaido expressway soil in Japan which indicated high impact on soil improvements. Sharma et al. (2019, 2020) studied on using a consortia of bacteria to improve soil strength whilst Zhang et al. (2020) applied MICP to achieve soil enhancement.

Sharma et al. (2021) provides a remarkable review study for different types of biogeotechnical procedures that were used for liquefaction mitigation in sands. Martinez et al (2022) utilized a study on biological organisms and systems interaction with soil and their capability to stabilise efficiently. Ongpaporn et al. (2022) conducted a case study for soil-slope stabilization by using soil bioengineering enhancements at Surat Thani Province in Southern Thailand. The results indicated the bioengineered soils reached appropriate shear condition regarding failure-control. Wani & Mir (2022) stated that the biogeotechnical techniques are eco-friendly and sustainable in the environment which could replace traditional treatment methodologies. The biogeotechnics provide more effective results and less environmental disruptions. Jiang et al. (2022) provide an extensive overview on bio-mediated soil improvement based on MICP treatments. The researchers referenced around one hundred studies published over the past five years, to provide an appropriate understanding of one of the biogeotechnical aspects. Figure 1 provides an example of MICP for sustainable biogeotechnics.

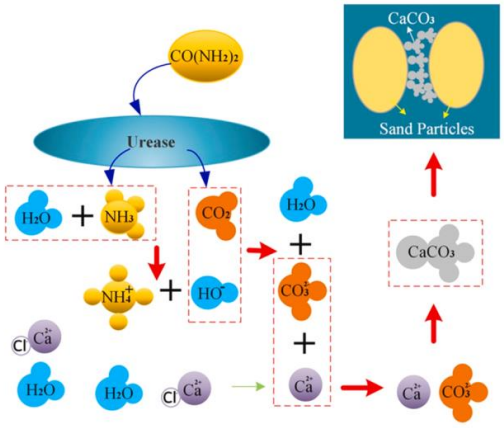

Figure 1: An example of chemical reactions of soil modification (J Zhang et al, 2023)

3 BIOGEOTECHNICS IN SUSTAINABLE ENVIROMENTAL GEOTECHNICS

In engineering practice, biogeotechnics can be applied in a variety of ways (Shackelford & Jefferis, 2000). For example, plants can be used to prevent erosion and stabilise slopes, while microorganisms can be used to break down pollutants in contaminated soils (Lai et al., 2021). Biogeotechnics is a promising field that offers many benefits for both the environment and human society. By utilising the power of living organisms, it has the potential to make construction and engineering projects more sustainable, non-harmful, less destructive, safer, and environmental friendly; while also providing a host of other benefits such as improved soil stability, water quality and biodiversity (Wang et al., 2020).

The objective of biogeotechnics in environmental geotechnics is to create engineered, sustainable, resilient infrastructure and dynamic projects that improve the quality of life for people and the environment. This is achieved by using natural systems and processes, such as plants and microorganisms, to manage resources such as water, air, and soil, and to minimize the environmental impact of human activities (Jefferis et al., 2014; Chittoori et al., 2020; Lai et al., 2021).

In general, application of biogeotechnics has specific benefits compared with conventional treatment methods. In fact, biogeotechnics is considered as a potential alternative or complementary approach to conventional treatment methods for various environmental issues. The main advantages that can be highlighted are given below (Terzis & Laloui, 2019; Chittoori et al., 2020; Mavroulidou & Shah, 2021; Lai et al., 2021):

Cost-effectiveness: Biogeotechnical solutions can be cost-effective compared to conventional treatment methods, particularly in the long run. For example, using plants to stabilize soil slopes or treating contaminated soil can be cheaper than using heavy machinery to install retaining structures or excavating contaminated soil.

Sustainability concept: Biogeotechnics is a sustainable approach that utilizes natural systems and processes to address environmental challenges. This approach can be more environmentally friendly than conventional methods, which may involve the use of chemical treatments or the excavation of large amounts of soil.

Resilience: Biogeotechnical solutions can promote resilience by creating self-sustaining ecosystems that can adapt to changing environmental conditions. For example, using plants to stabilize slopes can create a stable root network that can withstand soil erosion and slope failure.

Aesthetics: Biogeotechnical solutions can enhance the aesthetics of a site by creating natural landscapes and habitats that blend with the surrounding environment. This can be particularly important in areas where the visual impact of a treatment method is a concern.

Community Engagement: Biogeotechnical solutions can provide opportunities for community engagement and education, particularly when they involve the use of plants or other living organisms. This can help promote environmental awareness and stewardship in the local community.

4 CHALLENGES, OPPORTUNITIES AND PERSPECTIVES

Biogeotechnics is an interdisciplinary field that involves the application of ecological and geotechnical principles to the design and construction of sustainable infrastructure. There are various challenges and opportunities that are faced with developing such technologies. It can be said that biogeotechnics has not yet found its place in the industry; but is receiving attention as using such solutions to environmental improvements has promises for a bright future on geotechnical projects. However, biogeotechnical procedures has certain limitations, and perspectives which need to be also considered. In this section several challenges and potential opportunities of biogeotechnics are summarized.

4.1 Challenges to overcome

Some of the challenges that biogeotechnics faces are summarized below (O'Donnell et al., 2016; Kavazanjian, 2018; DeJong & Kavazanjian, 2019; Li et al., 2020; Ejezie et al., 2021 and Mavroulidou et al., 2022):

Soil erosion and sedimentation control: These techniques can be used to design and construct sustainable infrastructure that reduces soil erosion and sedimentation, thereby overcoming negative impacts on water quality and aquatic ecosystems.

Climate change: Biogeotechnics can be utilized to design and construct sustainable infrastructure that is resilient to the impacts of climate change, such as sea level rise and increased frequency and intensity of extreme weather events.

Integration of infrastructure and ecosystem: These techniques can be applied to design and construct sustainable infrastructures that are integrated with natural ecosystems, rather than conflicting with them, and to balance engineering, environmental and socio-economic aspects.

Innovation in materials: Advancement in bio-based materials, soil bioengineering, and the integration of these techniques with traditional techniques is a challenge that needs to be considered for biogeotechnics.

Site-specific considerations: The application of biogeotechnics principles and techniques is highly site-specific, and requires a thorough understanding of the local soil, hydrological, and ecological conditions. This can make it challenging to generalize and apply biogeotechnics solutions to other sites.

Long-term maintenance: Many biogeotechnical solutions, such as bioengineered slopes, require regular monitoring and maintenance to ensure they remain effective over the long-term. This can be a significant challenge, particularly in remote or inaccessible locations.

Field trials using biogeotechnics have been conducted in various settings to test the effectiveness of this approach in addressing different environmental challenges. Below are some examples of field trials using biogeotechnics (DeJong & Kavazanjian, 2019; Li et al., 2020; Ejezie et al., 2021):

Soil stabilization concept: Field trials have been conducted to test the use of vegetation to stabilize slopes and prevent erosion. For example, a study conducted in Spain tested the use of grasses and legumes to stabilize slopes in a road embankment. The study found that the vegetation cover reduced soil erosion and improved slope stability.

Bioremediation concept: Field trials have been conducted to test the use of plants and microbes to remediate contaminated soil and groundwater. For example, a study conducted in the UK tested the use of willow trees to remediate contaminated soil at a former gasworks site. The study found that the trees effectively removed pollutants from the soil.

Climate change adaptation concept: Field trials have been conducted to test the use of vegetation to mitigate the impacts of climate change, such as reducing the urban heat island effect. For example, a study conducted in the US tested the use of green roofs to reduce the surface temperature of buildings. The study found that the green roofs reduced the surface temperature of buildings significantly.

4.2 Opportunities for application

Several highlighted potential opportunities have been identified for biogeotechnics which involve sustainable development and eco-solutions for infrastructure and environmental projects (Mohan et al., 2006; O'Donnell et al., 2016; Azarafza & Ghazifard, 2016; Kavazanjian, 2018; Liu et al., 2019; Yue et al., 2020; Azizpour et al., 2020):

Bioremediation: Using microorganisms and plants to clean up contaminated ground, soil, and water.

Erosion control: Using bioengineering techniques, such as vegetation and soil bioengineering, to control erosion and stabilise slopes.

Climatological change: Using biogeotechnical approaches to adapt infrastructure to the effects of climate change, such as sea level rise and increased storm intensity.

Transportation: Using biogeotechnical solutions to improve the sustainability of transportation infrastructure, such as using green roofs and living walls to reduce the urban heat island effect and improve air quality near transportation corridors.

Landscape design: Using biogeotechnical principles to design sustainable and resilient landscape, such as using natural drainage systems, eco-buildings, and vertical gardens to manage stormwater and improve air quality.

Biomimicry: Using biogeotechnical techniques to imitate natural systems, such as using self-healing concrete, which mimic the self-healing properties of certain plant species, in construction projects.

Slope Stabilization and erosion control: Using plant cover and soil bio-engineering to control erosion and stabilise slopes.

Adapting infrastructure to climate change: Using biology and geotechnological approaches to adapt infrastructure to the effects of climate change, such as sea level rise and increased storm intensity.

Designing sustainable and resilient landscape: Biogeotechnics aims to design sustainable and resilient landscapes, such as using natural drainages to manage stormwater and improve air quality.

Minimizing the environmental impact of mining: Biogeotechnics aims to minimize the environmental impact of mining operations using vegetation to stabilize mine tailings and rehabilitate disturbed land.

Improving water management: Using environmentally compatible systems to improve water management, such as using constructed wetlands and rain gardens to improve water quality and reduce flooding.

Improving the construction material behaviour: using biogeotechnics helps to improve soil aggressiveness behaviour such as sulphate attack which is required to modify the construction materials like concrete or using galvanized wires and plastics. The latter materials increase the environmental damage which is produced by geotechnical activities.

Green infrastructure: Using biogeotechnical techniques to design and construct eco-green roofs, rain gardens, vertical walls, and other forms of green infrastructure that can improve water management, reduce urban heat island effects, and enhance urban biodiversity.

Buildings: Using biogeotechnical techniques to design sustainable buildings, such as using green roofs and living walls to improve thermal insulation and reduce the urban heat island effect and using natural ventilation systems to improve indoor water and air quality.

4.3 Perspectives

The perspectives of biogeotechnics vary depending on the implemented applications. Several general perspectives can be classified as follows (Azarafza & Ghazifard, 2016; Dalal et al., 2017; Kavazanjian, 2018; Liu et al., 2019; Yue et al., 2020; Azizpour et al., 2020):

Sustainability: it creates more sustainable infrastructure and environmental projects. This includes using natural systems to manage resources such as water, air, and soil, and minimizing the environmental impact of human activities.

Resilience: it creates more resilient geo-environmental projects that can adapt to changing conditions, such as climate change.

Innovation: it is a relatively new and emerging field that offers new and innovative solutions to environmental geotechnics problems.

Multidisciplinary tasks: it is a multi-disciplinary science that brings together expertise from different fields such as biology, ecology, geology, and civil engineering.

Cost-effective actions: it is a cost-effective way to create sustainable and resilient infrastructures, and environments as it often involves using natural systems that are often self-sustaining and self-regenerating.

Community-focused activities: it creates geo-environmental projects that are more responsive to the needs of local communities and that can improve the quality of life for people who live and work in these areas.

Nature-based process: it is a nature-based approach to geotechnical projects, which uses natural processes and organisms to solve engineering problems and create sustainable solutions.

Integrated approach: it is an integrated approach to infrastructure and engineering projects, which considers the interconnections between the different elements of a project and their impact on the environment and society.

Holistic: it is a holistic approach to engineering projects, which considers the different components of a project, such as the physical, chemical, and biological processes, and how they interact with each other.

Short versus Long-term impacts: it takes a long-term approach to infrastructures and geotechnical projects, which considers the short-term/long-term effects of a project on the environment and society, and how it can be sustained over time.

Collaborative: it is a collaborative approach to geotechnical projects, which involves working with different stakeholders, such as communities, government agencies, and private sector companies, to create sustainable solutions.

Adaptive: it is an adaptive approach to infrastructure and environmental projects, which considers the uncertainty and variability of natural systems and allows for changes and adjustments over time.

5 CONCLUSIONS

Biogeotechnics provides an important advancement in geotechnical engineering and soil improvements. It uses the biological organisms and living matter to modify the engineering properties of soil and increase the stability behaviour of a soil in order to accomplish its functions. A plethora of application examples are provided by researchers. By utilizing this biological/geo-environmental understanding, innovative geotechnical application solutions are emerging which lead to reducing the geotechnical impacts on ecosystems and the environment.

As results, it can be stated that biogeotechnics utilizes the eco-friendly strategies to reduce the ground destruction, engineering in harmony with the environment, geotechnical compatible schemes, and more respect to eco-systems regarding the modifications, improvements, investigations, and this has remarkable advantages.
The UN sustainable development goals demand a reduction in the construction impacts on the environment and this includes a clarion call for development of mitigations for the negative ecological/environmental effects of geotechnical projects. Governmental bodies and authorities

worldwide have been challenged to craft the legal frameworks and implement them properly. In the meantime, engineers can embrace biogeotechnics as it can play a key role in delivering the UNSUG2030 and net zero carbon. Providing the reliable and non-destructive procedures that improve engineering aspects of soils (the ground) and mitigate the impact of geotechnical activities is one of the functions that is expected from biogeotechnics.

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