Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-316

Geotechnics in the circular economy - contributions and challenges

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ABSTRACT

The effects of climate change that we have been experiencing and the increasing perception of citizens that natural resources are finite highlight the inevitability of making the society more sustainable. Therefore, the need to promote the transition from a Linear Economy to a Circular Economy model, and to implement this transition in different sectors of the economy have become topical issues. This paper presents the author's perspective on the circular economy in the construction sector and some challenges and potential contributions of civil and geotechnical engineering towards its implementation are outlined. The effective transition to a model of greater circularity in construction industry implies great technical and scientific challenges, encompassing multidisciplinary collaborations. Geotechnics having typically an early position in the construction process can have a crucial role. This paper aims to point out the relevance of geotechnical engineering to the circular economy as a tool to achieve the sustainable development.

Keywords: Sustainable development, Circular economy, Circularity in Geotechnics, Sustainability

1 INTRODUCTION

The European Commission (EC) published in December 2015 an Action Plan for the Circular Economy, bringing terms such as "Circular Economy" or "Carbon Neutrality" to the agenda. Based on the work done since 2015, the EC has recently (March 2020) adopted a new Circular Economy Action Plan, considering it as one of the main pillars of the European Green Deal, the new roadmap of Europe for sustainable development (EC, 2020). This new Action Plan focuses on the design and production phases, to ensure that the resources are kept in the economy for as long as possible. It sets out a forward-looking strategy to create a cleaner, more sustainable and more competitive Europe.

The EC intends to launch concrete measures in the different sectors of activity that use the largest amount of resources and where the potential for circularity is high, as is the case of the construction industry. As far as the construction industry is concerned, the EC plans to launch a new Strategy for the Sustainability of the Built Environment (EC 2020).

As a consequence of the above-mentioned EC actions, it became quite common to hear political and governmental authorities, the media, technicians and researchers highlighting the need to promote the transition from the Linear Economy model to a Circular Economy, and to implement that transition in the various sectors of the economy. However, in the construction industry, the changes are still very limited and there is a long way to be travelled.

It should be kept in mind that the circular economy in the engineering, architecture and construction sector goes far beyond recycling and recovery of construction and demolition (C&D) waste. The implementation of a circular economy approach in this sector requires promoting the recovery of the resources, keeping them in the economy as long as possible, and minimising the need for new consumption of materials and energy.

The most recent developments, the technical and scientific studies and the dissemination initiatives within the circular economy in the built environment, as well as the Action Plan itself, are very focused on buildings and on the construction products. Despite this evidence, Geotechnical Engineering may provide a significant contribution to make the construction industry more sustainable. Thus, this paper presents a perspective on possible contributions of Geotechnics to the circular economy and sustainable development. It is worth noting that it is not an exhaustive analysis and reflects only the author's view on the subject.

As the 2030 Sustainable Development Goals (SDGs) are the basis of the circular economy, those in which Geotechnics can make a greater contribution are highlighted. Then, the concept of circular economy is briefly presented and its application to the construction industry is detailed. Potential contributions of geotechnical engineering to sustainability and the circular economy are finally pointed out.

2 SUSTAINABLE DEVELOPMENT GOALS

The citizens' current perception that natural resources are finite, as well as the effects of pollution and climate changes, have made sustainable development an imperative goal that today's society has to achieve. In this context, the United Nations (UN) have proposed the Sustainable Development Goals (SDGs) considered as "*a universal call to action to end poverty, protect the planet and improve the lives and prospects of everyone, everywhere*" (UN, 2015).

The SDGs adopted by all UN Member States in 2015, as part of the 2030 Agenda for Sustainable Development, Figure 1, define the priorities and ambitions to achieve the global sustainable development and encompass diverse areas that affect the quality of life of all citizens and future generations.

Among the 17 SDGs schematically represented in Figure 1, those to which Civil Engineering, in general, and Geotechnics, in particular, can make significant contributions through their actions in society are highlighted:

- Ensure access to water and sanitation for all (SDG 6), contributing to their provision and sustainable management.
- Ensure access to affordable, reliable, sustainable and modern energy (SDG 7), through its actions in the design and construction of the required structures and infrastructures.
- Build resilient infrastructure, promote sustainable industrialization and foster innovation (SGG 9), introducing and promoting new technologies to increase resource and energy efficiency in built environment.
- Make cities inclusive, safe, resilient and sustainable (SDG 11), through all its actions in the built the environment, transportation and urban planning.
- Ensure sustainable consumption and production patterns (SDG 12), reducing the consumption of natural resources and the impact of the construction activities on the environment and increasing the energy and material efficiency of the built environment.
- Take urgent action to combat climate change and its impacts (SDG 13), through all the above-mentioned actions, contributing to the reduction of greenhouse gas emissions.

Figure 1. *The 17 Sustainable Development Goals adopted by all UN Member States (UN, 2015)*

Although the SDGs previously identified are considered to be those to which the most relevant contributions can be made, Civil and Geotechnical Engineering can also contribute, in a more indirect way, to the remaining Sustainable Development Goals, namely to:

- SDG 1 (No poverty), SDG 2 (Zero hunger) and SDG 8 (Decent work and economic growth), through the creation of jobs and contributing to the improvement of quality of life.
- SDG 3 (Good health and well-being), contributing to reduce road accidents and to improve the quality and availability of potable water and sanitation.
- SDG 14 (Life below water), contributing to reduce marine pollution and to preserve coastal areas.
- SDG 15 (Life on land), contributing to reduce pollution, to combat desertification and to restore degraded lands.

As citizens, all of us should also contribute to the quality of education (SDG 4), gender equality (SDG 5), reduce inequalities (SDG 10) and to the peace, justice and strong institutions (SDG 16).

3 CIRCULAR ECONOMY

3.1 Brief description of the concept

First of all, it should be pointed out that the circular economy can be seen as a tool to meet the challenges introduced by the establishment of the aforementioned Sustainable Development Goals.

The circular economy represents a key alternative to the linear economic model: extraction – production/manufacturing – use/consumption – disposal, which is still prevalent in today's society. The linear economy model is based on the assumption that natural resources are widely available, easy to obtain and the cost of disposal is low. While this model of the economy has been crucial to the industrial development enabling high levels of economic growth, currently it is not a sustainable model, as we are outgrowing the planet's capacity.

The circular economy is, by definition, a strategic and operational approach that is based on the reduction, reuse, recovery and recycling of materials and energy, enhancing the value and extending the lifetime of products, materials and resources in the economy. In practice, the circular economy model implies reducing waste to a minimum, implying that when a product reaches the end of its life, its materials are kept within the economy wherever possible (European Parliament, 2018) - Figure 2. It aims to add value to the resources, keeping them in the economy for as long as possible, and minimising the need for new consumption of raw materials and energy (Ellen MacArthur Foundation, 2015a).

Figure 2. *Circular economy model (European Parliament, 2018).*

It is important to highlight that the circular economy goes far beyond waste management and recovery. Its implementation requires that natural resources are managed efficiently throughout the entire life cycle, and that products are designed for maximum reuse of their materials or components (Figure 2).

Lacy and Rutqvist (2015) consider that the circular economy implementation should be based on five business models: circular supply chains, recovery and recycling, product lifetime extension, sharing platforms and products as services.

There are several models in the literature to explain and exemplify the concept of circular economy that cannot be exhaustively addressed in this paper. However, the Ellen MacArthur Foundation's view on the concept of circular economy should be presented (Ellen MacArthur Foundation, 2015a; 2015b), albeit in a very simplified way, which is set out in the following paragraphs.

The circular economy should be restorative and regenerative and aiming to kept products, components and materials at their highest level of utility and value throughout their life cycle, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2015a). Resources should be regenerated in the biological cycle and valued in the technical cycle, as schematised in the well-known "butterfly" diagram.

According to Ellen MacArthur Foundation (2015a), the circular economy rests on three principles:

1) Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows;
2) Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.
3) Foster system effectiveness by revealing and designing out negative externalities.

Applying the first principle implies the selection of renewable or better-performing resources using efficient technologies and processes. The second principle means designing for remanufacturing and recycling to keep materials and components circulating in the economy. The third principle comprises reducing damage to systems and managing externalities, such as land use, air, water pollution and the release of toxic substances (Ellen MacArthur Foundation, 2015a).

The three principles above mentioned can translate into six actions: Regenerate, Share, Optimise, Loop, Virtualise and Exchange – the ReSOLVE framework (Ellen MacArthur Foundation, 2015b).

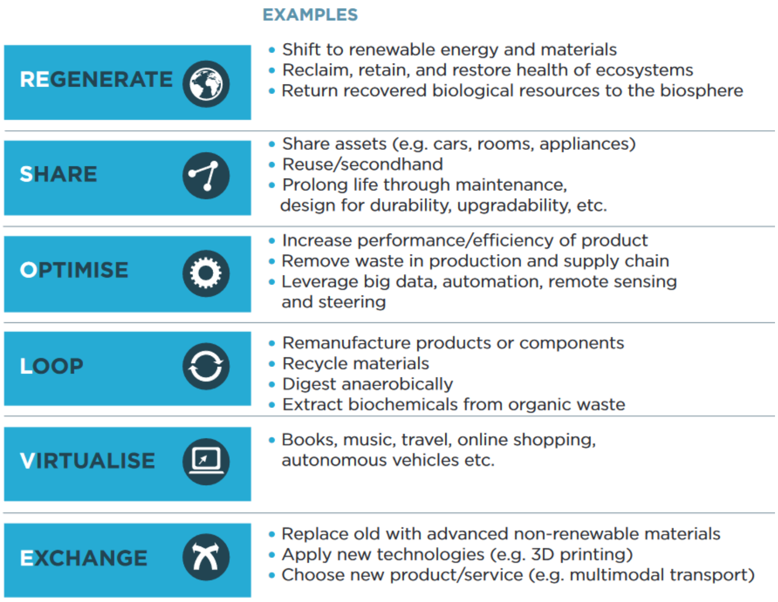

Figure 3. *The ReSOLVE framework (adapted from Ellen MacArthur Foundation, 2015b).*

3.2 Circular economy in the built environment

Lately the designation "Circular Construction" has been used by some stakeholders when referring to the implementation of the principles of circular economy in the construction sector. This terminology seems to the author somewhat inaccurate, as it may be connected to the geometric shape of the construction and not to the principles that are intended to be adopted. Thus, in this paper the terms "circular economy in the built environment " or "circular economy in the construction" are preferred.

Figure 4 shows a simplified schematic representation of the circular economy in the built environment, seeking to meet the circular economy model proposed by the European Parliament (2018) and presented in Figure 2. The diagram is a simplified model, since the potential interconnections between the different phases of the life cycle of the structures or infrastructures are not represented, but highlights some of the key points to be considered in those phases.

When designing a building or other structure the modular construction shall be envisaged, foreseeing the dismantling, the reparability of the construction elements and the demolibility at the end of its lifetime. The design should enhance the extension of the lifetime of buildings and infrastructures, considering different uses and sharing of spaces and, envisaging the use of recycled materials.

In the construction stage, waste prevention, sorting and recycling are very crucial. During operation and use, water recycling, energy saving and the use of renewable energies should be promoted. The sharing of facilities should be encouraged, reducing the need for new spaces and equipment.

In maintenance and rehabilitation operations, the focus on intelligent maintenance and renovation, avoiding unnecessary demolitions, are key procedures to be adopted. When demolition is needed, sorting of waste, materials and components that can be reused should be promoted.

Products and components manufacturing should seek to make them more durable, repairable and recyclable, using by-products and recycled materials whenever possible.

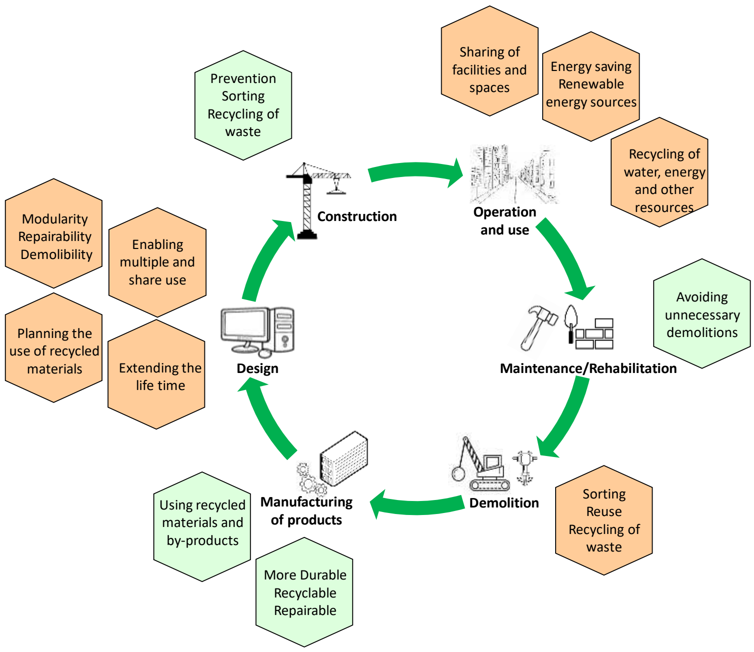

Figure 4. *Simplified schematic representation of circular economy in the built environment (adapted from Vieira, 2021).*

4 GEOTECHNICS IN THE CIRCULAR ECONOMY

4.1 General

As highlighted by Basu et al. (2015) geotechnical projects interfere with several social, environmental, and economic issues and improving the sustainability of geotechnical processes can represent a very significant contribution to sustainable development.

The main objective of practising geotechnical engineers is to ensure that projects are carried out with less uncertainty/risk, more quickly, using more efficient and cheaper methodologies and with due respect for sustainability and environmental protection. Those who engage in research and technological innovation should seek to provide the knowledge and understanding that allow problems to be solved and that enable projects to be realised based on the aforementioned assumptions (Cardoso, 2016). Thus, it can be said that geotechnical engineering can contribute significantly to the sustainable development and the circular economy in the construction field. It is worth recalling that all structures and infrastructures are based on or within the ground.

Applying the concepts of the circular economy in geotechnical engineering can assume multiple forms, all of them seeking a more efficient use of resources and energy, waste production minimization and reduction of the environmental impacts of products, works or operations. The following sub-section presents some of these forms and highlights related works that have been emerging in the literature.

4.2 Contributions and challenges

The preservation of the natural resources, the minimisation of waste production, the reduction of our dependence on fossil fuels and the decrease of greenhouse gas emissions are some of the main goals to be achieved by the implementation of the circular economy in different fields. Bearing in mind these purposes, some actions through which geotechnical engineering can contribute to bring the engineering, architecture and construction sector closer to the principles of circular economy are highlighted:

- Use of efficient and environmentally friendly materials in geotechnical works, namely by-products and industrial wastes (ashes and slags from waste incineration or steelworks, recycled rubber granulates, etc.), recycled aggregates from waste and geosynthetics produced from recycled polymers;
- Use of environmentally friendly ground improvement techniques, including the use of industrial waste or by-products for soil stabilisation;
- Use of sustainable solutions using geosynthetics, namely the application of geosynthetics in prevention and remediation of ground or coastal erosion and in the construction and rehabilitation of transport infrastructure, dams and canals;
- Minimisation of the environmental impacts of the construction activities, by promoting the sustainability of the geotechnical projects (less energy and resource consumption);
- Use of geothermal energy through the use of thermoactive geostructures (foundations, tunnels, containment structures), allowing the reduction of the dependence on fossil fuels and of greenhouse gas emissions;
- Development of more efficient and economic underground construction techniques, enabling the sustainable use of underground space (transport infrastructure, underground storage of energy, hazardous waste and carbon dioxide);
- Development of innovative equipments and technologies to allow a better characterization of the ground and thus improve the quality of geotechnical projects (note that unforeseen ground conditions are one of the most common causes of problems that occur both during construction and operation phases);
- Reclamation of contaminated land prioritising more environmentally efficient in-situ remediation techniques;
- Rehabilitation and reuse of foundations (whenever technically feasible);
- Landfill mining and sustainable use of wastes;
- Mitigation of climate change effects (soil erosion, floods, heavy rains, earthquakes, …) particularly through the stabilisation of embankments and slopes and designing geotechnical structures for more adverse conditions.

All the above actions represent major challenges for geotechnical and geoenvironmental engineering. Nevertheless, they have the potential to respond to the actions recommended by the ReSOLVE framework (Figure 3), in particular to the first four: Regenerate, Share, Optimise and Loop.

Basu et al. (2015) point out that sustainability in civil and geotechnical engineering can be considered as a dynamic equilibrium between Engineering design, Economy, Environment, and Equity (four Es) - Figure 5. Thus, geotechnical engineering has to address the challenges of the circular economy with this equilibrium in mind.

The most part of papers found in the literature on sustainability in Geotechnics is related to the use of alternative materials, such as wastes or residues, in geotechnical projects. The feasibility of the use of Construction and Demolition (C&D) wastes as recycled aggregates in base and sub-base layers of roadways has received great attention in recent years from several researchers around the world (Poon

& Chan, 2006; Arulrajah et al. 2014a; Mehrjardi et al. 2020; Lu et al. 2021; Vieira et al. 2022; Pereira & Vieira 2022). Other materials, such as recycled glass (Arulrajah et al. 2014b) or mixture of different types of waste (Saberian et al. 2019; Perera et al. 2020; Maghool et al. 2022) have also been studied as alternatives for pavement base/subbase applications.

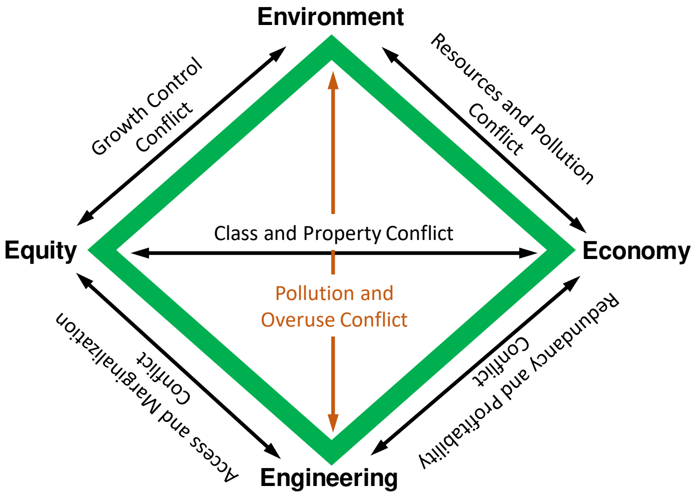

Figure 5. *Four Es of sustainability in engineering projects according to Basu et al. (2015).*

Recovered plastic and C&D waste blends as railway capping layer materials were studied by Arulrajah et al. (2020). The use of steel slag aggregates (Delgado et al. 2021), tire-derived aggregates (Fathali et al. 2016; Esmaeili et al. 2017), steel-slag mixed with ruber ortire-derived aggregate (Khoshoei et al. 2021; Alves et al. 2023) and mixtures of steel furnace slag, coal wash and rubber crumbs (Indraratna et al. 2021) in ballast tracks have been investigated towards a more sustainable railway construction industry.

The use of recycled C&D wastes as alternative pipe backfilling materials (Rahman et al., 2014; Vieira et al. 2017), in landfill cover layers (Ng el al. 2019) and in geosynthetic reinforced structures (Santos et al. 2013; Arulrajah et al.2013; Vieira et al. 2016) has also been researched. The feasibility of using other wastes, such as spent coffee grounds, as non-structural embankment fill material was also reported by Arulrajah et al. (2014c).

The long-term behaviour of geosynthetic reinforced structures constructed with recycled C&D materials has also been studied (Ferreira et al. 2022; Vieira el al. 2023). A full-scale geosynthetic-reinforced structure with two reinforced slopes (one reinforced with a PET geogrid and the other with a high-strength geotextile), 3 m high, was constructed using a fine-grain recycled C&D recycled material and

Figure 6. *Full-scale geosynthetic-reinforced structure built with recycled C&D waste (Ferreira et al. 2022; Vieira el al. 2023).*

is being monitored (Figure 6). The results of both the laboratory study and the monitoring of the full-scale model have been encouraging.

Soil stabilisation with wastes and by-products has also attracted great interest from several researchers. Recently, Rezaei-Hosseinabadi et al. (2022) reported the use of steel slag as granular column for ground improvement in geotechnical projects. Recycled concrete aggregates were used by Shourijeh et al. (2022) for stabilization of clay reinforced with recycled tire polymer fibers and glass fibers. The stabilization of PET plastic-demolition waste blends using fly ash and slag-based for application in light traffic road bases/subbases was studied by Arulrajah et al. (2021).

In general, the use of waste or by-products as alternative to more conventional materials has shown adequate or acceptable technical performance. However, it is important to emphasise the imperative need to assess the environmental, economic and social impacts related to their application, through proper sustainability assessment tools.

The contribution of geosynthetics to the achievement of sustainable development goals has been strongly emphasised by the International Geosynthetics Society (IGS), in particular through its recently established Sustainability Committee. According to the IGS, the application of geosynthetics allows the reduction in energy consumption and gas emissions (e.g. through the reduction of excavation works, transport of materials and maintenance requirements); preservation of surface and groundwater and safeguard from contamination (e.g. landfill lining and containment of waste, preservation of potable and irrigation water, …); reduction or replacement of other construction materials (e.g. sands, aggregates, …); environmental protection and resilience increase (e.g. coastal protection, green roof construction, earthquake resistant infrastructure, …); contribution to the economic growth and social welfare (e.g. faster and more cost effective construction); and, ensures unequalled solutions (e.g. construction over otherwise unusable ground conditions, …). The papers published by Touze (2021; 2022) and Palmeira et al. (2021) provide valuable insights into the potential contributions of geosynthetics to sustainability.

Although a search in Science Direct (in January 2023) for the keywords "reuse of foundations" had not identified any scientific publication on the topic, the reuse of existing foundations has been attracting increased interest among the technical and scientific communities, with at least one conference dedicated to the subject planned for 2023.

5 CONCLUSIONS

This paper briefly presents the author's perspective on the circular economy in the construction sector and some challenges and potential contributions of civil and geotechnical engineering towards its implementation are outlined.

Examples of studies carried out in more recent years seeking out greater sustainability in the geotechnical interventions were presented. The purpose of this paper is not to review the conclusions of these studies, so they have only been mentioned. Notwithstanding it should be noted that most of the studies found in the literature do not assess the environmental, societal and economic impacts of the proposed solutions. Life cycle analyses are of paramount importance to assess the sustainability of the new solutions or technologies and should be encouraged.

A detailed analysis and discussion of the potential environmental, societal and economic benefits of implementing circular economy principles in civil and geotechnical engineering would greatly enhance the content of the paper, but the limitations inherent to a conference publication made its accomplishment unfeasible. The analysis of those potential benefits will be covered in a future publication.

The implementation of the circular economy principles in the engineering, architecture and construction sector raises major technical and scientific challenges. It will enhance new markets and business models, but the effective transition to a more circular economy implies significant changes at several levels and must involve the different stakeholders. It requires a change of mindset since the circular economy goes far beyond waste recovery and use of green building materials. As it involves different fields (materials, energy, geotechnical and structural engineering, thermal, acoustics, ...), the circular economy in the construction industry requires, more than in most sectors, inter and multidisciplinary collaborations. Geotechnical engineering is clearly within the range of disciplines that can provide significant contributions.

6 ACKNOWLEDGEMENTS

This work was financially supported by Base Funding—UIDB/04708/2020 of CONSTRUCT - Institute of R&D in Structures and Construction - funded by national funds through the FCT/MCTES (PIDDAC).

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