

Comparing CO₂ emissions between two ground improvement schemes: prefabricated vertical drains vs. geosynthetic encased columns

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ABSTRACT: The design engineers' responsibility is not limited to finding a safe solution but includes considering also the environmental impact of the suggested design. In many cases a soil improvement becomes necessary when constructing an embankment on soft subsoil conditions. One of the alternative soil improvement methods is installing Prefabricated Vertical Drains (PVD). A more recent alternative is installing Geosynthetic Encased Columns (GEC). In this study a comparison was made on the environmental impact both methods will create. As a measure of the environmental impact, carbon dioxide (CO₂) emissions is taken. For this purpose, a case study was taken which was suggested for the project Sande bypass, which was a major rail expansion project for the Jade Weserport hinterland link in Germany. For the same site a design with both PVDs and GECs was provided. For the comparison of CO₂ emissions transportation distances of geosynthetic products and granular column materials have been estimated. Since GECs can use any granular material as fill, only one hauling distance was estimated. The designer had planned an additional surcharge load to avoid residual porewater pressure which can cause settlements during the operation of the road even after a reasonable waiting time with the PVDs installed. Obviously, this additional surcharge load must be transported and later excavated and disposed of. Therefore, a comparison based on the unit area was not possible. Therefore, the CO₂ emission was compared for 1 m width of the embankment. It was determined that the GEC alternative produces a smaller CO₂ footprint than the PVD alternative.

KEYWORDS: CO₂ emission, Soil improvement, sustainable design, PVD, GEC.

1 INTRODUCTION

In the realm of geotechnical engineering, the stabilization of soft soils beneath embankments is a critical challenge. Two prevalent ground improvement techniques - Prefabricated Vertical Drains (PVDs) and Geosynthetic Encased Columns (GECs) - have been extensively utilized to enhance the load-bearing capacity and mitigate excessive settlement in such soils. While both methods have proven effective, their environmental impacts, particularly concerning CO₂ emissions, are often overlooked. This article aims to compare the carbon footprints of PVDs and GECs, providing insights into their sustainability profiles.

2 SUSTAINABILITY

Sustainability has become part of our daily lives as our living environment is being threatened by climate change. Despite the recent efforts to reduce the related risks, environmental sustainability has still not been achieved. As a result, human-induced climate change is already affecting people, ecosystems, and livelihoods around the world. The fact that the construction industry is one of the largest users of global resources and is a major contributor of pollution places a heavy responsibility on the construction industry to reduce its load from the viewpoint of sustainability (Yoo, 2023). Hence, beside the technical and economical items in a design, there is huge demand for a sustainable design which aimed for reduction of energy consumption and emission of climate related gases like CO₂ and CH₄. However, sustainability is a complex concept. In the charter for the UCLA Sustainability Committee, sustainability is defined as: "the physical development and institutional operating practices that meet the needs of present users without

compromising the ability of future generations to meet their own needs, particularly with regard to use and waste of natural resources. Sustainable practices support ecological, human, and economic health and vitality. [web1].

In order to achieve a sustainable future in the building industry, Asif et al. (2007) suggest the adoption of a multi-disciplinary approach covering a number of features such as: energy saving, improved use of materials, material waste minimization, pollution and emissions control etc. There are certainly many ways in which the current nature of building activity can be controlled and improved to make it less environmentally damaging, without reducing the useful output of building activities.

While analyzing the sustainability of components for geotechnical soil improvement projects, often only the greenhouse gases are considered. And CO₂ emissions dominate the produced greenhouse gases. Occasionally, depending on the type of natural soil, methane (CH₄) or nitrous oxide (N₂O) can play a role. Or if heavy machinery with cooling systems is employed, there could be minor Hydrofluorocarbons (HFC) emissions, especially if the equipment leaks. In summary, for all the activities including geotextile production, the kgCO₂eq. values have been used, which incorporates all potential greenhouse gases. Since kgCO₂eq. emissions contribute significantly to climate change, it is essential to understand the carbon footprint of construction materials and processes. Therefore, CO₂eq. emissions have become a major concern in the construction industry, and there is an increasing interest in finding ways to reduce the carbon footprint of various construction materials and methods. Here are a few examples from the literature highlighting the comparison of CO₂eq. emissions for utilizing a geosynthetic to achieve the same goal with the use of geosynthetics or without.

3 COMPARED SOIL IMPROVEMENT SCHEMES

3.1 Prefabricated vertical drains

PVDs, also known as formerly as wick drains, are geosynthetic materials designed to accelerate the consolidation of soft, saturated soils by providing a path for pore water to escape (Rixner et al., 1986; Sakleshpur, 2024; EN 13252, 2016; EN 15237, 2007; Chu et al., 2004). Typically composed of a polypropylene core wrapped in a geotextile filter, PVDs are installed vertically into the ground to facilitate drainage. Their primary application is in areas where rapid consolidation is required, such as beneath embankments or in land reclamation projects. The installation process involves minimal soil disturbance, and the materials used are lightweight, contributing to lower transportation-related emissions.

3.2 Geosynthetic encased columns

GECs are an advanced ground improvement technique that involves encasing granular columns with a geosynthetic material, typically a geotextile, to enhance their load-bearing capacity and reduce settlement (Alexiew and Raithel, 2014; Pandey et al., 2022; Cengiz and Guler, 2018; Raithel and Kempfert, 2000). This method is particularly effective in very soft soils where conventional stone columns may not be feasible. The geosynthetic encasement provides lateral confinement, preventing bulging and improving the overall stiffness of the column. While GECs offer significant performance benefits, their environmental impact is influenced by the materials used for the geosynthetic encasement and the construction processes involved.

4 DESIGN OF THE COMPARED GROUND IMPROVEMENT SCHEMES

4.1 Project and Properties of the foundation soil

As an example of the comparative consideration of the two foundation systems, a construction project from northern Germany "ABS Sande", which was implemented in the years 2018 - 2022, is used. This is the construction of a new 2-track railway line to connect the Jade-Weser-Port in Wilhelmshaven as a bypass of the village of Sande. In the course of the route, the Ems-Jade Canal has to be crossed. For the bridge structure, ramps of approx. 9m height are required, for which special measures were required to reduce settlement and increase stability due to the thick organic soft layers of clay and peat.

The soft layers of soft organic clay (so-called "Klei") and peat were explored in thicknesses of approx. 7 to 15 m and are characterized by low shear strengths of $\phi' = 15^\circ$ to 20° or $c_u = 13 - 20$ kPa and low stiffness of $E_s = 0.3 - 1.0$ MPa. Due to these low characteristic values, subsoil improvement measures are required for the foundation of the ramp embankments.

4.2 Prefabricated vertical drain design

As part of an earlier design, soil improvement was planned for the foundation of the railway embankments by preloading and consolidation with the participation of PVD's. For this purpose, it was planned to build the pre-load dam with temporary berms (see Fig.1) and to reinforce the dam basis with a 3-layer geotextile reinforcement with a design strength of $R_d = 3 \times 600 = 1800$ kN/m, corresponding to a short-term strength of about $R_k = 3 \times 1300$ kN/m. In anticipation of the settlements, the pre-load embankment was planned with an overfill of $h_{\text{ü}} = 3.0$ m above the later track position. Due to the low stiffness of the existing soft layers, settlements of a size of approx. $s = 2.5$ m

were to be expected with this variant, which had to be taken into account in the form of a correspondingly larger amount of sand.

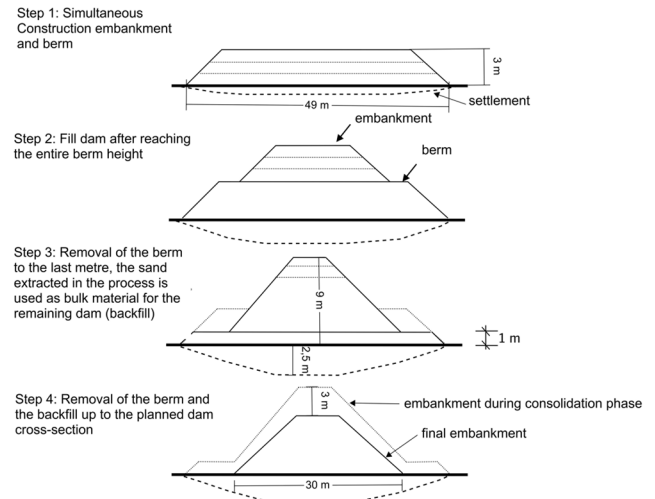


Fig.1: Sequence of works on the construction of the PVD dam

4.3 Geosynthetic encased columns

As part of an optimized design, a foundation on GEC was planned and executed for the dam (see Fig2). As a result, the required sand masses could be significantly reduced due to the possible elimination of the lateral berms, the lower pre-load and the lower settlement. Only in the immediate transition to the deeply founded bridge abutments, a larger pre-load was chosen to anticipate the settlements. In addition, due to the increase in stability due to the load-bearing effect of the GEC, the horizontal geotextile reinforcement could be significantly reduced, a single-layer geogrid with a short-term strength of $R_k = 1000$ kN/m was therefore sufficient.

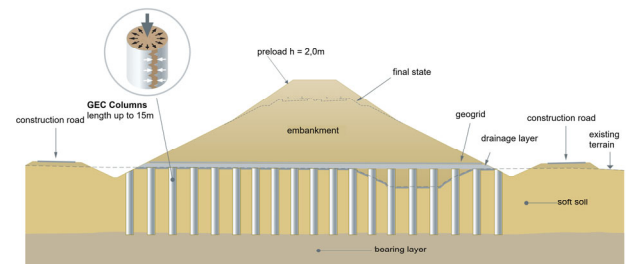


Fig.2: Cross section of GEC embankment

5 CO₂ EMISSION CALCULATIONS

The functional unit chosen for the CO_{2eq} emission comparison was 1 m width of the embankment. This choice was adapted because a comparison per square meter of the foundation surface was not possible due to the fact, that the width of the embankment was designed to be wider temporarily for the PVD alternative. All the unit CO_{2eq} emissions related to different products and operations have been summarized in Table 1.

Table 1. The unit CO_{2eq.} emissions for various operations and products.

Source of CO ₂ emission	Reference	Unit	kgCO ₂
Laying out of soil and compaction	CAT 815	m ³	0.84
Excavation of soil and loading to trucks	Lewis and Hajji (2012)	m ³	1.48
Hauling of earth materials and geosynthetics with 16–32 metric ton lorry	Ecoinvent Centre.(2024)	ton-km	0.172
Diesel burned in construction machine	Ecoinvent Centre.(2024)	Liter	3.34
GEC installation (0.8 m diameter)	Average from several Installers	m	5.50
Geosynthetic (for horizontal reinforcement and column encasement)	EPD	kg	4.63
PVD production	Dr. Erten	m	0.55
PVD installation	Average from several Installers	m	1

5.1 CO_{2eq.} emission for the PVD alternative

For the PVD solution, as can be seen in Figure 1, the base width of the embankment is larger, and the temporary fill is higher. The reason for this is to assure stability, create a uniform settlement under the final embankment fill and also make sure that all secondary settlements have been taken care of. For the whole project we assumed that the unit weight of the fill is 18 kN/m³. By using this unit weight and the cross sections given in Figure 1, the amount of fill required for the construction of the actual fill was estimated as 2916 kN/m. The additional fill quantities required for the PVD solution have been estimated as: *i)* The amount of fill to widen and heighten the embankment beyond the actual embankment was 990 kN/m, *ii)* In addition to this fill, to provide stability in the initial phase, berms are constructed which require another 1188 kN/m, *iii)* later these berms will be excavated and added to the top of the temporary embankment to further increase the total load.

Therefore, a total of 2180 kN/m fill needs to be transported to the site and compacted. Later 1188 kN/m of this fill will be again excavated (the berms) and carried to the top of the embankment and compacted. Eventually all the 2180 kN/m fill have to be excavated and transported away. For the excavation the required CO_{2eq.} was estimated considering that a 200 hp dozer is used, the material is sand and the average haul distance for the dozer to haul the excavated material to the truck is 50 m. For the compaction of the soil it was assumed that CAT 815 compactor is utilized.

The PVDs are installed with a triangular pattern and center to center distance of 0.8 m. Each PVD is installed to a depth of 8 m. Hence in total, for a 1 m deep slice of the embankment, the total PVD installed will be 1015 m. To determine the CO₂ emission related to the PVD production, we have considered the filter geotextile and core separately. The filter geotextile has to have minimum weight of 136 g/m² according to the South Carolina Department of Transportation's Supplemental Technical Specification for Prefabricated Vertical Drain with Fabric (Kitowicz, 2024). Literature cites that the filter geotextile can have a weight 100 to 200 g/m². For a similar geotextile the EPD (2) states that the CO_{2eq.} per kg of polypropylene nonwoven geotextile was 2.54 kg. That means if we assume a unit weight of 150 g/m², per m length of the PVD, the production of the filter geotextile produces approximately 0.095 kgCO_{2eq./m}. The core has to have a minimum weight of 56 g/m according to Kitowicz (2024). Literature sites that the

total weight of PVD varies between 100 and 300 g/m. Therefore, we assumed that the core weights on average 150 g/m

Of course, the CO_{2eq.} emissions related to the production, transportation and installation of the PVDs have been included in the total emissions. It was calculated that for the 1 m width slice of the embankment a total of 1015 m of PVD will be installed. Furthermore, the CO_{2eq.} emission due to drainage gravel that need to be placed on top of the natural soil and the suggested horizontal geosynthetic reinforcement has been included in the analyses.

5.2 CO_{2eq.} emission for the GEC alternative

For the GEC alternative there is also a small overburden fill that will be placed on top of the final embankment. The amount of this additional fill was determined as 419 kN. The total length of the GECs installed for 1 m width of the embankment was 147 m. Of course, the CO_{2eq.} emissions related to the production of the geosynthetic encasements, transportation of them and installation of the GEC columns have been included in the total emission. Although not absolutely necessary, a drainage gravel layer is also considered in this solution. This drainage gravel has a lower volume compared to the PVD alternative, because the width at the base of the embankment is smaller in the GEC solutions.

6 CONCLUSIONS

When all the activities that cause a CO₂ emissions are considered and the CO₂ emissions due to the geosynthetic products are incorporated into the analysis the following comparison given in Table 2 and Figure 3. Because it is not possible to know from which distance the earth material to build the additional fill for the embankment is unknown, three different transportation distances have been chosen.

Table 2. CO_{2eq.} emissions for PVD and GEC alternatives for 1 m width of embankment

		Soil Improvement with PVD	Soil Improvement with GEC
Transportation Distance of additional earth fill (km)	10 km	6053	4062
	20 km	6607	4134
	30 km	6981	4206

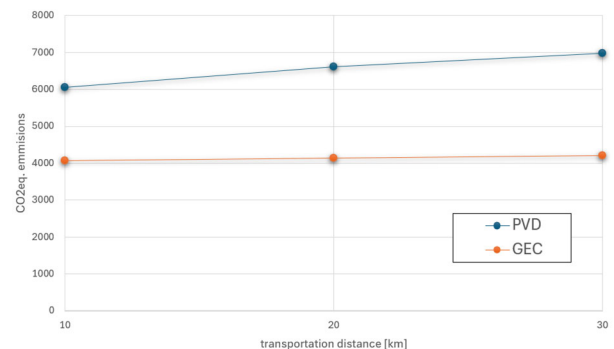


Fig. 3: CO_{2eq.} emissions for PVD and GEC alternatives for 1 m width of embankment

It is clear from the comparison given in Table ZZ, that the GEC alternative causes less CO_{2eq.} emission. In order to check whether the reduction of the fill material necessary is the dominant cause, the CO_{2eq.} emissions for the geosynthetic inclusions have been evaluated. Here the CO_{2eq.} emission include the CO_{2eq.} emission caused for the production of the

PVDs versus geosynthetic encasement and also the installation of these. The results are given in Table 3.

Table 3. Comparison of CO_{2eq.} emissions for production and installation of the geosynthetic products and their installation

	CO _{2eq.} / m width of embankment		
	Geosynthetic Encasement/PVD Material and Transportation of it	Installation of Vertical Elements	TOTAL
PVD	660	1015	1675
GEC	1807	811	2618

As can be seen from Table CC although the GEC encasement obviously uses much more geosynthetic compared to PVD, because the total number of installation per unit surface area is much less than the PVD, the total CO_{2eq.} emissions are not that significantly different.

The design of the horizontal reinforcement for the GEC application serves to distribute the embankment load between the GEC columns and therefore a single layer of reinforcement with a tensile strength of 1,000 kN/m was sufficient. However, in the case of soil improvement with PVDs, the horizontal deformation has to contribute to the stability of the embankment itself until consolidation is completed and therefore the design had foreseen three layers of horizontal reinforcement was necessary each with a tensile strength of 1,300 kN/m. Considering that the base width of the temporary embankment for the PVD solution is also wider, the GEC solution allows for a much smaller CO_{2eq.} emission.

So, as a conclusion it can be stated that the GEC solution for soil improvement can be an alternative to PVD installation to reduce the CO_{2eq.} emissions. Of course, this analysis was made with certain assumptions. For each case, depending on the in-situ soil conditions and the various transportation distances the analysis should be repeated to demonstrate its advantage.

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