Life cycle assessment and design methodology of sustainable grs structures using marginal fill and high performances draining geogrids

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Abstract. Traditional Geosynthetics Reinforced Soil (GRS) systems often use high-quality, expensive imported granular fill as structural backfill. Limited local availability of such fill leads to resource depletion and increased carbon emissions from quarrying. The construction industry is now seeking sustainable alternatives to maintain GRS integrity while mitigating environmental impacts. The use of locally available marginal fill offers a sustainable solution, conserving natural resources, reducing waste and disposal costs, and lowering the carbon footprint. When combined with high-performance draining geogrids that integrate reinforcement with drainage, this approach enhances both environmental sustainability and structural performance. The dual function of this system improves the longevity and stability of structures, reducing maintenance needs and playing a key role in project life cycle assessment. This study presents a detailed comparative Life Cycle Assessment (LCA) between traditional reinforced slopes and environmentally friendly GRS structures, providing information on structural design methodology to boost confidence in using marginal fills for reinforced soil systems.

1 Introduction

In recent years, construction has increasingly prioritized environmental awareness, driven by global recognition of the negative impacts of human actions on the environment. The European Union urges the construction industry to explore sustainable alternatives that minimize environmental impact and resource exploitation. Reinforced soil structures in civil engineering typically use granular fills due to their high shear strength and ability to dissipate pore water pressures. While cost-effective, procuring these high-quality soils often involves sourcing from distant quarries, impacting sustainability. Using locally available marginal soil minimizes resource exploitation and improves project cost-effectiveness. However, these soils have low permeability, high plasticity, low shear strength, and excessive pore pressure build-up. Their use in reinforced soil structures is feasible with adequate drainage design and high-performance engineered draining geogrids to ensure stability and performance. Developing a geocomposite that combines reinforcement and drainage functions enables the construction of sustainable and environmentally friendly GRS structures using locally

available cohesive fill.

2 Design methodology of draining geogrids

The draining geogrid presented in this article (see Figure 1) comprises both longitudinal and lateral strips. While the function of the lateral strips is only to maintain the grid geometry, it is the longitudinal strips that give the product its uniqueness, which resides in a dual function: reinforcement and drainage. The reinforcement function is provided by the core of high-tenacity polyester yarns encased in a polyethylene sheath, while the draining function is found in the shape of the longitudinal strips. These strips are manufactured to create a drainage channel covered by a laminated non-woven geotextile. The geotextile acts as a filter that allows water to pass through the channel while preventing clogging from fine soil particles. This allows for quicker dissipation of pore pressure within the cohesive soil, thus accelerating the soil consolidation process.

These engineered draining geogrids have been successfully used for decades in numbers of projects following the design method published by Naughton et al. (2001). The hydraulic transmissivity of these improved geogrids has been measured in laboratory according to the relevant ISO 12958-2010 (see Figure 2).

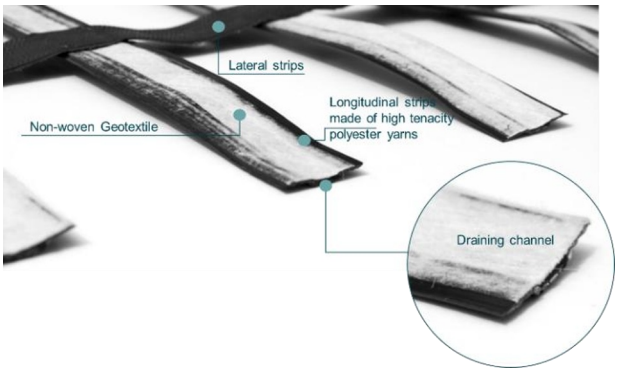

Figure 1. Draining geogrid cross sectional structure

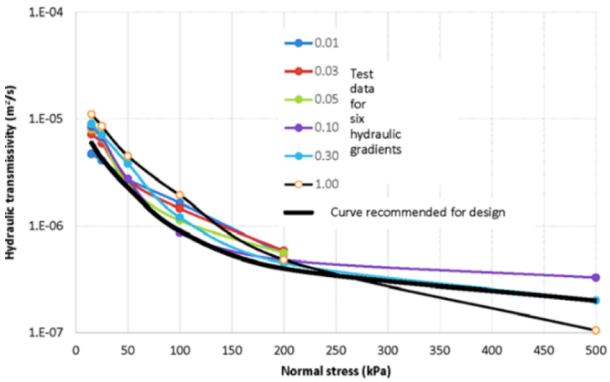

Figure 2. Hydraulic transmissivity of the draining geogrid as a function of the normal stress (kPa) and hydraulic gradient

The results of this intensive test campaign brought to an improved methodology developed by Giroud et al. (2014), for designing reinforced slopes using cohesive fill. This approach incorporates the consolidation properties (coefficient of volume compressibility, m_v, and coefficient of consolidation, C_v) of the marginal fill to determine vertical spacing between draining geogrid layers and construction rate feasibility. The developed method consists of:

1. Calculating the necessary hydraulic transmissivity of the draining geogrid and the time required for rapid pore pressure dissipation.
2. Assessing the stability and settlement of the reinforced structure, following conventional multilayer design principles for walls or slopes (Limit Equilibrium Method).

Naughton et al. (2015) further validated this methodology showing that reinforced soil structures can be constructed from most low permeability fills once careful consideration is given to the drainage properties of the fill and the vertical spacing of the draining geogrid.

3 Comparative life cycle assessment for GSR with conventional and sustainable design

Draining geogrids have been extensively used in projects with marginal fill worldwide. The following section compares two cases of embankment construction (200m length) for developing a real estate area: Case A (see Figure 3), involves a conventional GRS structure using imported free-draining granular fill from 100km quarry, while Case B uses a sustainable GRS with site won marginal fill and draining geogrids (see Figure 4). The site is located in the northeast of Banbury, UK, in a sandy silts area (classified as Dyrham Formation and Charmouth Mudstone - Class 2A and 2B (SHW, 2009)), where the excavated site won marginal fill need to be either reused or disposed of in a landfill. The nearest disposal site is located at almost 100 km northeast from the project location. The embankment consists of a 70° reinforced soil steep slope with an average height of 6.08m.

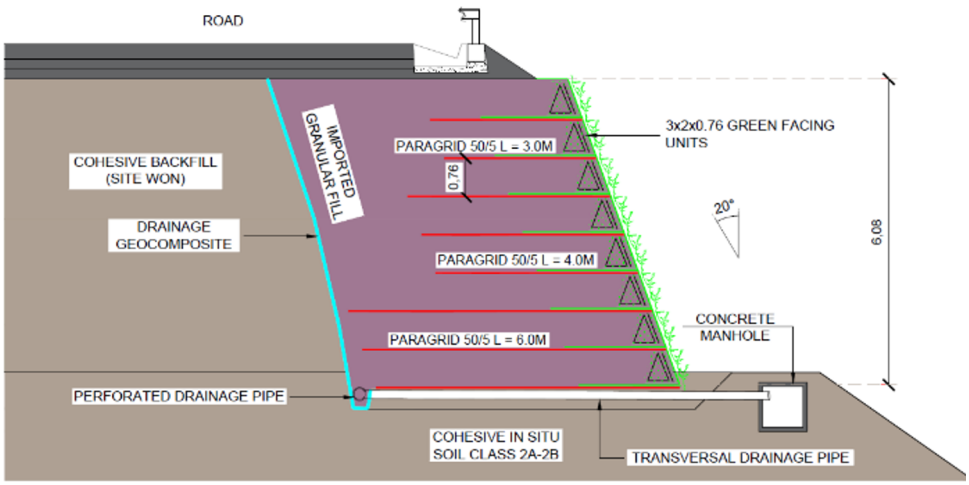

Figure 3. Details of reinforced soil slope with imported granular fill and geogrid (Case A).

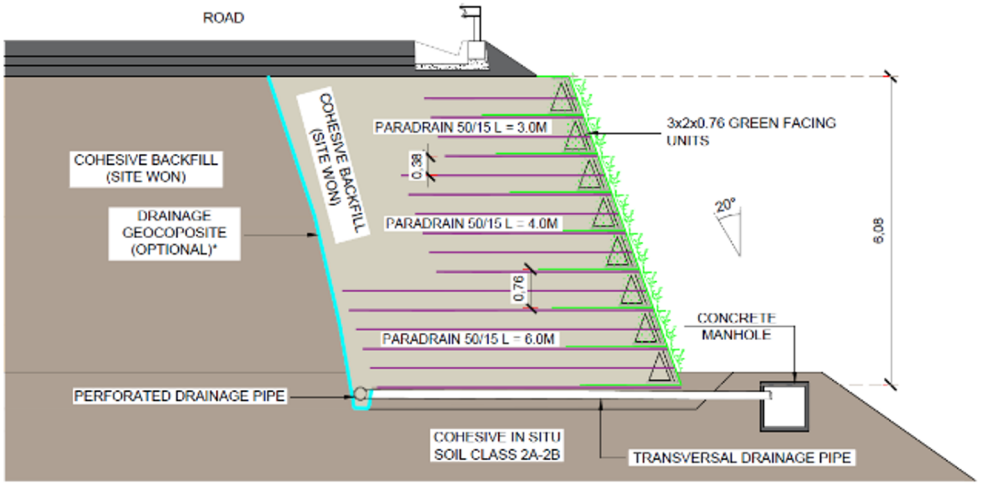

Figure 4. Details of reinforced soil slope with site won marginal fill and draining geogrid (Case B).

Stability checks using the limit equilibrium method for both Case A and Case B showed comparable results in terms of reinforcement length, tensile strength (T_{char} = 50kN/m), and safety factors. For Case B, the Giroud et al. (2014) design methodology was followed to determine the hydraulic transmissivity of the draining geogrid and the time required for pore pressure dissipation. A 90% degree of consolidation was considered, meaning excess pore water pressure would dissipate to 10% of its initial value. Stability checks accounted for residual excess pore water pressure, with ru = 0.23 at the end of construction and ru = 0.02 at the end of consolidation. In Case A, residual pore water pressure was not considered within the structural fill due to its high shear strength and lack of significant pore pressures.

Case B required more geogrids (15,600 m² of draining geogrids vs. 7,800 m² of standard geogrids), but the LCA results in favor of Case B in terms of environmental impact. The assessment used a "cradle to construction" system boundary, excluding maintenance, operation, and disposal. The LCA study, conducted using SimaPro software and the CML-IA baseline V3.05 method, considered the following impact categories: Abiotic Depletion - Minerals & Fossil Fuel, Global Warming Potential, Ozone Layer Depletion, Photochemical Oxidation, Acidification Potential, and Eutrophication Potential.

4 Conclusions

Table 1 below displays the input data that was considered for the comparative study. The data is based on the applicable design specific to the site requirement. The variation in material used, logistics, and energy consumption required for each Case has been considered for the comparative study.

Table 2 shows that the higher impacts of Case A are caused by the emissions and resource consumption related to the transportation of the imported granular fill to the site and the transportation to disposal of the site won material not used for the construction.

Table 1. Inputs for comparative Life Cycle Assessment of Cases A & B: Case A: with imported granular backfill and Paragrid geogrid, and Case B: with site won cohesive backfill and Paradrain geogrid.

Item Description	Unit	Case A*	Case
Reinforced Soil Slope height	m	6.08	6.08
Reinforced Soil Slope length (functional unit)	m	200	200
Slope face units	nos	550	550
Soil reinforcing geogrid	m2	7,800	15,600
Backfill soil (imported granular)	m3	12,090	-
Backfill soil (site won cohesive)	m3	-	12,090
Disposed excess site won soil	m3	11,054	-
Transportation by 24 Ton truck for Geogrid	tkm	3,360	6,720
Transportation by 24 Ton truck for imported granular	tkm	2,342,400	-
Transportation by 24 Ton truck for disposal of excess site	tkm	2,198,400	-
Diesel used in construction machineries	MJ	10,944	16,416

Table 2. LCA results in tabular format (ReCipe 2016 method): Case A: with imported granular backfill and Paragrid geogrid, and Case B: with site won cohesive backfill and Paradrain geogrid.

Environmental Impact category	Short Form	Unit	Case A*	Case B**	Reduction in
Global warming Potential	GWP	Kg CO2	9.93E+00	3.06E+00	69.17
Ozone Depletion	ODP	Kg CFC-	3.22E-11	1.32E-11	58.93
Acidification Potential	AP	Kg mol	2.51E-02	7.68E-03	69.38
Eutrophication Potential-	EP-fr	Kg P eqv.	2.37E-05	1.46E-05	38.43
Eutrophication Potential-	EP-	Kg N eqv.	8.28E-03	4.19E-03	49.35
Eutrophication Potential-	EP-	Kg N eqv.	6.56E-02	4.76E-02	27.43
Abiotic depletion – Non-	ADP-	Kg Sb eqv.	5.27E-07	2.68E-07	49.22
Abiotic depletion - Fossil	ADP-	MJ	3.90E+02	2.10E+02	46.13

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