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Multi-objective optimization of geosynthetic reinforced soil structures

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Abstract. Optimization models for reinforced earth structures such as foundation pads, bridge abutments, and embankments based on the Eurocode standard are presented. The developed optimization models, which take into account construction costs and environmental footprint, are used to determine an optimal design for each earth structure. The optimization model uses discrete variables, making the results more suitable for actual construction practice and fully exploiting the geotechnical and structural capacity of earth structures with geosynthetic reinforcement. The multi-objective optimization was performed to find a set of solutions that represent the best trade-off between construction cost and environmental footprint. The results show that the correct selection of geosynthetics leads to a significant reduction in costs and environmental impact. The general observation that emerges from the multi-objective optimization is that when designing the earth structures using geosynthetic reinforcements, due to the discrete set of variables, there are not so many optimal solutions that the designer can choose from. The entire optimization process is illustrated with the help of a numerical example. This study can help engineers to select earth structure and geosynthetic reinforcements that are economical and sustainable.

1 Introduction

Geosynthetic reinforcement has demonstrated its economic efficiency in various engineering structures, providing cost-effective solutions while maintaining structural integrity [1,2]. This text discusses the use of geosynthetics in various applications, including road pavements, pile embankments, reinforced pad foundations, and geosynthetic reinforced soil (GRS) bridge abutments. While much attention has been paid to the cost effectiveness of geosynthetic reinforcements, their environmental impact is rarely studied. The objective of this paper is to demonstrate the benefits of using geosynthetic reinforcement from both an economic and environmental perspective.

Geosynthetics play a critical role in flexible pavement design (see, Fig 1a), especially when built on weak subgrades. Researchers have found that incorporating geosynthetic reinforcement allows for a reduction in the thickness of the base and sub-base layers. Jelušič et al. [3] proved that for subgrades with lower California Bearing Ratio (CBR) values (up to

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4%) pavement structures with geosynthetic reinforcement are the optimal solution. The cost advantage lies in the savings achieved through reduced material volume and excavation, making geosynthetic reinforcement more economical than thicker unbound base courses or subbases. In addition, geosynthetic reinforcement enables cost-effective pavement designs for higher traffic loads.

Geosynthetics have proven to be extremely efficient in the design of pile embankments (see, Fig 1b). By inserting geosynthetics into the soil at the base of an embankment, the load is distributed across the tops of the pile caps, bridging the soft soil between the piles. This proper application of geosynthetics prevents embankment settlement and enhances stability. Jelušič and Žlender [4] emphasized that pile embankments with basal reinforcement using geosynthetics with higher short-term strengths and stiffness are more economically feasible, even with increased geosynthetic costs.

Reinforced pad foundations are another application where geosynthetics offer cost advantages. These foundations increase bearing capacity by providing confinement and tensile resistance, effectively distributing stresses, and preventing failure (see, Fig. 1c). Research [5] on the optimal design of reinforced pad foundations revealed that they are especially economically suitable for lower soil shear angles, lower horizontal loads, and heavier vertical loads. In a case study, the use of a reinforced pad foundation under a strip foundation was shown to reduce manufacturing costs by 42% compared to an optimal classical strip foundation.

Another reinforced soil structure, the geosynthetically reinforced soil abutment (GRS-BA), has also proven to be an effective solution for supporting bridge structures and is a competitive alternative to conventional reinforced concrete bridge abutments (see, Fig 1d). Extensively documented case studies have established that geosynthetic-reinforced soil (GRS) bridge abutments (BAs) exhibit strong performance characteristics when subjected to both static and dynamic loads, despite their uncomplicated and cost-effective design[6–10]. Damians et al. [11,12] outlined the methodology for conducting a sustainability assessment of retaining structures using an illustrative example aimed at selecting the most sustainable option among several retaining walls, such as conventional gravity and cantilever wall designs, as well as steel and polymeric soil-reinforced mechanically stabilized earth (MSE) walls of different heights. The findings from an environmental life cycle assessment (LCA) reveal that the GRS bridge system exhibits significantly reduced environmental impact compared to a conventionally constructed bridge using reinforced concrete of equivalent design [13]. The study conducted by Jelušič and Žlender [14] showed that the bridge abutment GRS is most economical for bridge spans of less than 14 m and wall heights up to 6 m, when the bridge structure consists of a reinforced concrete T cross-section. A full-size bridge supported by GRS bridge abutments was designed and constructed (see, Fig. 2), and based on an analysis of construction costs, it was found that conventional reinforced concrete abutments could cost up to five times the amount of an optimally designed GRS bridge abutment [15].

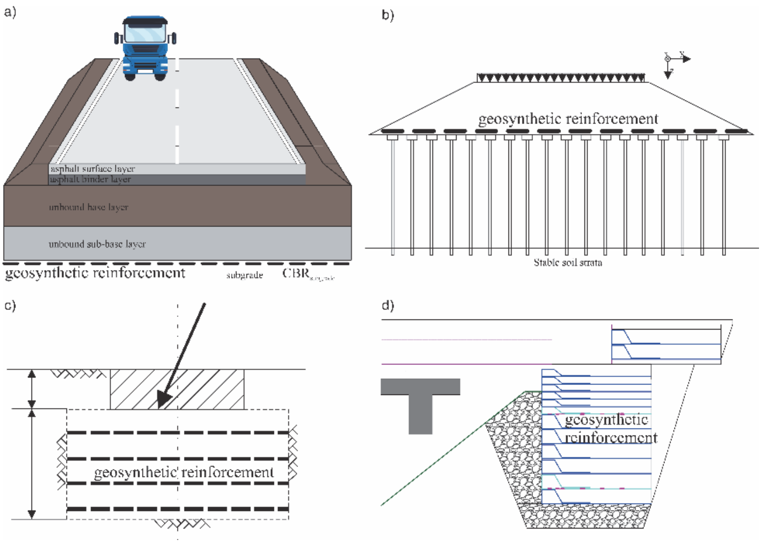

Fig. 1. Case studies of the cost effectiveness of geosynthetic-reinforced soil structures: a) flexible pavement, b) pile embankment, c) reinforced pad foundation, and d) GRS bridge abutment.

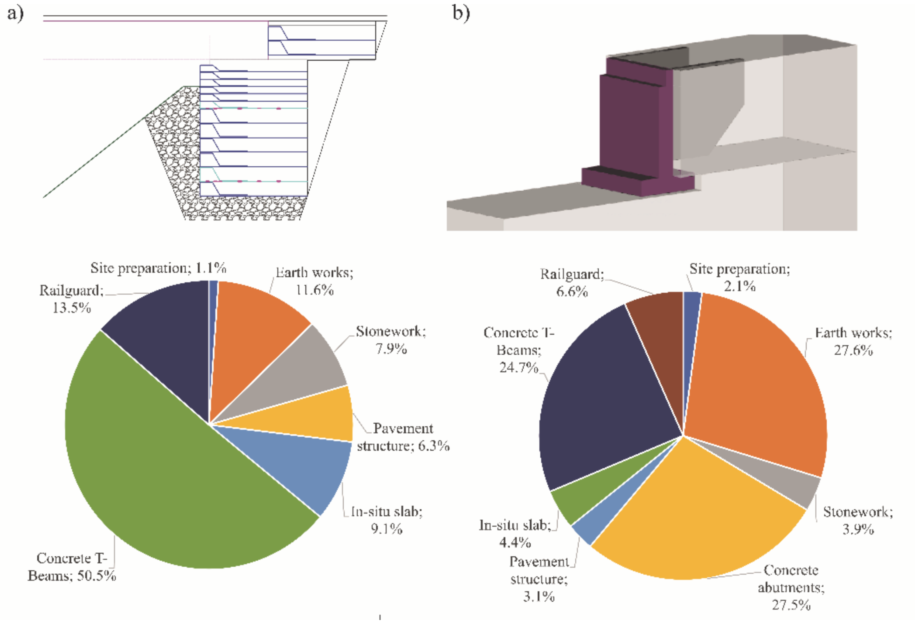

Fig. 2. Construction cost breakdown: a) GRS-BA and b) reinforced concrete abutment.

While the above research mainly focuses on increasing the cost efficiency of major engineering structures through the use of geosynthetic reinforcement, the benefits of using geosynthetics from an environmental perspective are rarely discussed. The concept of sustainable design of structures encompasses both cost and environmental impacts simultaneously. In much research on sustainable reinforced concrete design, objective functions have been developed to find the optimum cross-sectional dimensions and steel reinforcement arrangement that can support the applied loads with minimum cost, minimum CO_2 emissions, and maximum safety. Jelušič and Žula [16] have shown that the optimal design of the reinforced concrete cross-section considering the material cost as an objective function leads to a larger cross-sectional area of the concrete and a smaller area of the steel, compared to the optimization results when the CO_2 emissions are considered as an objective function. In addition, the optimal solution with the material costs as the objective function has a significantly higher reserve in the axial load-carrying capacity than the optimal design when the CO_2 emissions are chosen as the objective function. Fig. 3 shows that there are not so many optimal solutions from which the designer can choose due to the discrete set of variables in the optimal design of reinforced concrete sections based on multi-objective optimization. Only several points are displayed for the selected MEd-MEd state, each point represents a separate design solution.

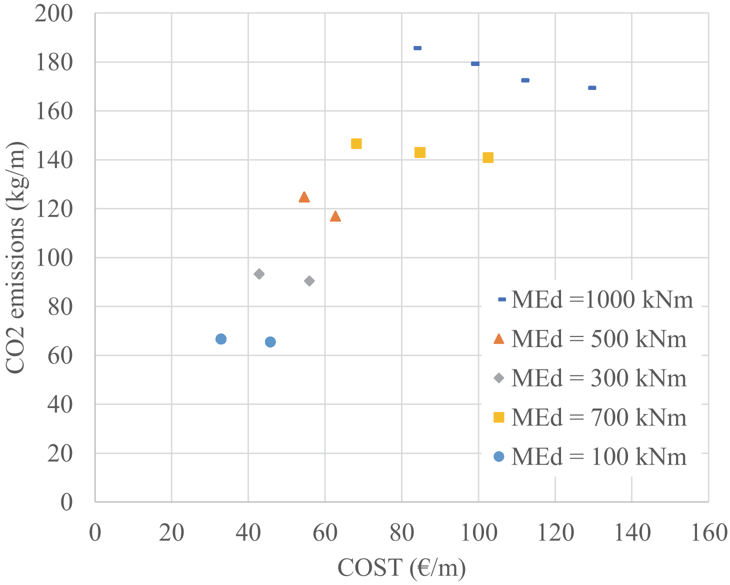

Fig. 3. Pareto front for a reinforced concrete circular cross section loaded with an axial load of N_{Ed} = 3000 kN for different applied bending moment M_{Ed}.

This paper presents the sustainable design of geosynthetically reinforced flexible pavements. A comparison was made between pavements with and without geosynthetic reinforcement in terms of design, optimal construction cost, and CO_2 emissions. The minimum California Bearing Ratio (CBR) value of the subgrade at which the use of geosynthetic reinforcement for pavement construction is economically and sustainably justified was determined. A holistic approach considering both economic and environmental aspects is essential for sustainable design, ensuring the longevity and resilience of geosynthetic reinforced soil structures.

2 Example of optimization of a geosynthetically reinforced flexural pavement structure

Consideration of environmental concerns in the construction of roads is of paramount importance. Aside from minimizing construction costs, conscious efforts should be made to reduce the environmental footprint associated with road pavement construction. This can be achieved by adopting sustainable practices, using environmentally friendly materials, and optimizing construction processes to reduce energy consumption and emissions. To effectively achieve the above objectives, it is essential to develop an optimization model. This model should include a cost objective function that considers construction costs and a carbon footprint function that evaluates environmental impacts. In addition, various constraints must be included in the optimization model to ensure that the pavement design meets the required standards and specifications. By incorporating these elements into the optimization model, engineers can attempt to create a pavement design that not only meets structural requirements, but also demonstrates environmental sustainability while minimizing construction costs. Two objective functions are determined for cost (see, Eq.1) and CO_2 emissions (see, Eq.2):

$$COST_{pav} = C_{exc} + C_{gc} + C_{fill,b} + C_{as,subs} + C_{fill,sb} + C_{as} + C_{ab} + C_{geo} \tag{1}$$

$$CO_{2,total} = CO_{2,exc} + CO_{2,fill,b} + CO_{2,as,subs} + CO_{2,fill,sb} + CO_{2,as} + CO_{2,ab} + CO_{2,geo} \tag{2}$$

The individual items of the objective functions are the cost or amount of CO_2 emissions from the ground excavation (C_{exc}, $CO_{2,exc}$), ground compaction (C_{gc}), unbound sub-base fill ($C_{fill,sb}$, $CO_{2,fill,sb}$), unbound base fill ($C_{fill,b}$, $CO_{2,fill,b}$), asphalt substrate ($C_{as,subs}$, $CO_{2,as,subs}$), asphalt surface layer (C_{as}, $CO_{2,as}$), asphalt binder layer (C_{ab}, $CO_{2,ab}$), and geosynthetics (C_{geo}, $CO_{2,geo}$). An optimization model was built to determine the minimum thickness of each pavement layer that still meets all conditions and consequently ensures sufficient performance over the intended 20-year period. The ESAL (traffic load) is the most important design parameter in pavement design, so a parametric analysis was determined for various combinations of parameters such as total number of ESALs (T_n) and California Bearing Ratio of subgrade ($CBR_{subgrade}$). The Table 1 show the optimally pavement design for subgrade $CBR_{subgrade} = 3\%$. Note that das represents the asphalt surface layer, d_{ab} represents the asphalt binder layer, d_b represents the unbound base layer, and d_{sb} represents the unbound sub-base layer. Fig. 3 shows that the use of geosynthetics is economically justified when the CBR of the subgrade is less than 5%, and that the use of geosynthetics is environmentally justified when the $CBR_{subgrade}$ is less than 6%.

Table 1. Optimal pavement design for subgrade $CBR_{subgrade} = 3\%$, with and without geosynthetic reinforcement.

Without geosynthetic reinforcement						**With geosynthetic reinforcement**				
T_n (ESAL)	$d_{as}+d_{ab}$	d_b	d_{sb}	COST	CO_2	$d_{as}+d_{ab}$	d_b	d_{sb}	COST	CO_2
(-)	(cm)	(cm)	(cm)	(€/m^2)	(kgCO_2/m^2)	(cm)	(cm)	(cm)	(€/m^2)	(kgCO_2/m^2)
1.00E+04	10	25	66	61.9	22.0	10	25	33	54.6	20.5
1.00E+05	10	25	66	61.9	22.0	10	25	33	54.6	20.5
1.00E+06	13	25	66	68.2	26.7	13	25	33	60.9	25.2
1.00E+07	22	25	66	87.0	40.9	22	25	33	79.7	39.3
1.00E+08	36	25	66	116.3	62.9	36	25	33	109.0	61.3

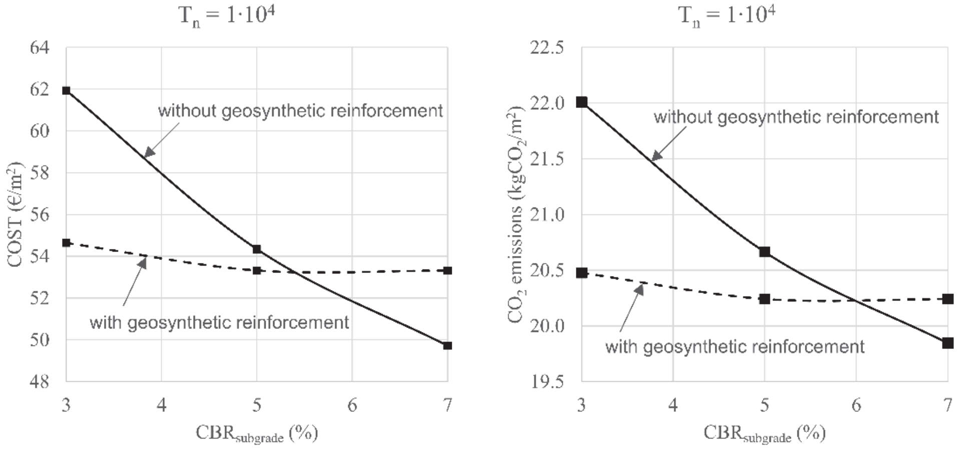

Fig. 4. Costs and CO_2 emissions of road pavements depend on the quality of the subgrade and the use of geosynthetics.

3 Conclusion

This paper addresses the importance of considering environmental aspects in the design of geosynthetic reinforced soil structures. To date, more research has been done to reduce construction costs and less to reduce environmental impacts, especially in geotechnical engineering. Even less research has been done to reduce costs and environmental impacts simultaneously. Multi-objective optimization should consider both cost and CO_2 emissions in the optimal design of geosynthetic-reinforced soil structures, since different materials have different unit prices and CO_2 emissions. The general observation that emerges from multi-objective optimization is that in the design of earth structures with geosynthetic reinforcement, there are not so many optimal solutions from which the designer can choose because of the discrete set of variables. This conclusion is consistent with the multiobjective optimization of structures composed of composite materials such as reinforced concrete. As an example of sustainable design, a flexible pavement was optimized considering both structural cost and CO_2 emissions in the optimal design. In addition, the impact of incorporating geosynthetic reinforcement was analyzed in terms of cost and CO_2 emissions. The geosynthetic-reinforced and the unreinforced pavements were optimized for different traffic loads and subgrade properties. The use of geosynthetics could lead to a 15% reduction in pavement construction costs and a 9% reduction in CO_2 emissions by reducing the thickness of the unbound layers. However, under favourable site conditions (e.g., subgrade CBR of 7%), the use of geosynthetics could also lead to an increase in road structure costs and CO_2 emissions.

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