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Displacement-based design method to increase sustainability of pile-supported embankments: Practical application

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ABSTRACT: Concrete piles and geosynthetic reinforcements are commonly used to reduce settlements at the top of embankments. The use of geosynthetic layers at the embankment bottom leads to several advantages: (i) faster construction, (ii) better control of differential settlements and (iii) a fewer number of piles is needed for equal admissible settlements at the embankment top. Because of the latter point, the use of geosynthetic reinforcement reduces the Embodied Carbon related to concrete. Unfortunately, since existing design methods for Geosynthetic-Reinforced and Pile-Supported embankments do not allow to calculate settlements at the embankment top, they cannot be used to optimize the number of concrete piles to increase sustainability. In this note, an innovative model for assessing settlements induced by the embankment construction process is applied to the preliminary design stage of a practical example. The mass of CO_2 saved by using geosynthetics and optimizing the number of piles is calculated.

1 INTRODUCTION

Civil engineering is enormously contributing to the consumption of both global energy reserves and raw materials such as gravel, sand, and water (Dixit *et al.* 2010). In a context where all civil engineers can have a major influence towards a more sustainable development, geotechnical engineers have a crucial role in highly increasing the sustainability of a project. In fact, geotechnical engineering is one of the key fields contributing to a sustainable development, since it faces a challenging dichotomy between delivering project goals (environmental, economic, and social) and maintaining sustainability (Abreu *et al.* 2008).

From a practical point of view, the exploitation of increasingly large areas of territory has led also to the construction of infrastructures under difficult geological and geotechnical conditions, requiring geotechnical engineers to find new (and not always "environmentally friendly") solutions. As an example, embankments for major infrastructures are more often realized in areas where soils are deformable and, to avoid unacceptable settlements, concrete piles are commonly employed as settlement reducers. Such "geo-structures", composed of embankment, foundation soil and concrete piles, are named Conventional Pile-Supported Embankments (CPSE). The rigid inclusion (i.e. the pile) causes the development of the "arching effect", that reduces the portion of embankment load transferred to the soft soil (alleviating differential settlements within the embankment), while stresses flow through the piles towards more competent soil layers. Depending on both the overall length of the infrastructure to be realized and the mechanical properties of the ground to improve, CPSE may require the installation of a huge number of concrete piles along different kilometers of infrastructure, leading to a huge outflow of both economic and environmental resources.

To further reduce settlements in CPSE, geosynthetic reinforcements (GR) are often installed at the bottom of the embankment. Studies on Geosynthetic-Reinforced Pile-Supported

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Embankments (GRPSE) have proven that the GR effectively increase the arching effect, leading to both a reduction of differential settlements as well as a reduction in the number of piles needed. This latter aspect is fundamental to increase the sustainability of the project, by reducing the Embodied Carbon (EC, which is defined as the carbon dioxide emitted during the manufacturing, transport, construction and the "end of life" of a material) related to concrete piles.

According to the actual standards (BS8006-1, 2010; EBGEO, 2010), the design of GRPSE is carried out in Ultimate Limit State (ULS) conditions, leading to extremely conservative estimation of the loads applied on GR and piles (Bhasi & Rajagopal 2015). Despite the very simplistic approach suggested by the standards, it is hard to use those methods to optimize the design of both piles and GR to reduce the number of piles (and EC) needed for GRPSE.

Furthermore, the standards do not allow for the estimation of settlements at the top of the embankment, even though King *et al.* (2017) recently stated that the assessment of settlements to ensure the serviceability of the infrastructure over its all lifetime is necessary. In this perspective, (Mangraviti *et al.* 2022) developed a displacement-based (DB) method for the estimation of settlements at the top of the embankment during the construction of GRPSE under drained conditions, validated against field tests in (Mangraviti *et al.* 2023a). The simplified method proposed by the authors applies for smooth end-bearing concrete piles located in the central part of the embankment. Based on this new DB method, Mangraviti (2022) conceived a simplified DB procedure to optimize the design of GRPSE (i.e. pile spacing and GR stiffness) in a preliminary design stage.

In this note, the procedure developed by Mangraviti (2022) is introduced (§2) and a practical application of the procedure is presented (§3), together with some concluding remarks (§4).

2 DB PROCEDURE TO INCREASE SUSTAINABILITY OF GRPSE

In this study, settlements induced by the embankment construction process in GRPSE (Figure 1a) are considered. When studying the mechanical behavior of the central part of the embankment, it is common in the literature to consider as representative one central axi-symmetric cell. The representative unit cell (Figure 1b) of diameter s, assumed to be equal to the pile spacing (different values can be considered in case of squared pile pattern) includes: (i) one pile of diameter d and length l, (ii) a homogeneous soft soil stratum of thickness l resting on a rigid bedrock, (iii) an embankment of which height h evolves during the construction process and (iv) the geosynthetic reinforcement laid at the embankment base. The pile shaft is assumed to be smooth (leading to a conservative estimation of settlements), and the construction process is assumed to occur under drained conditions.

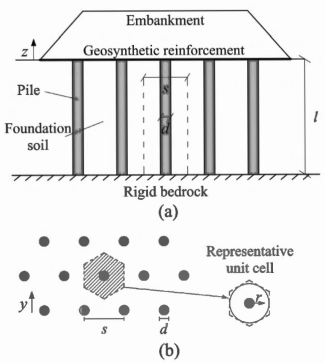

Figure 1. (a) Geosynthetic-reinforced and pile-supported embankment and (b) representative unit cell.

In Mangraviti *et al.*, (2023b), the mechanical response of the representative unit cell was modelled with finite difference numerical analyses by using simple constitutive models: the pile was assumed to be elastic, the GR was modelled as an elastic isotropic membrane (of axial tensile stiffness J) and the soil was modelled with non-associated elastic-perfectly plastic constitutive relationship with a Mohr-Coulomb failure criterion. This constitutive modelling, despite of its simplicity, can capture the main aspects of the mechanical processes taking place in the representative unit cell, which are:

a) the arching effect, that is the stress transfer mechanism towards piles occurring within the embankment (Terzaghi 1936);
b) the plane of equal settlements, that is the plane above which differential settlements are negligible (McGuire 2011);
c) the process height, that is the height of the portion of embankment where plastic shear strain accumulate during construction (di Prisco *et al.* 2020).

It is worth mentioning that, when the construction process is considered, the plane of equal settlements is where the increments of differential settlements are nil, even though differential settlements are larger than zero (Mangraviti *et al.* 2023b). According to di Prisco *et al.* (2020), differential settlements in CPSE stop increasing during construction when the height of the embankment is larger than a critical height value (h^*). The non-dimensional critical height (H^*) value is:

$$H^* = \frac{h^*}{d} = \frac{1}{2}\sqrt{\left[\frac{E_{oed,e}}{E_{oed,f}}\frac{l\,d}{s^2}\right]^2 + \frac{(s/d)^2 - 1}{\overline{k}\,\tan\phi'_{ss}}\left(\frac{E_{oed,e}}{E_{oed,f}}\frac{l\,d}{s^2}\right)} - \frac{1}{2}\left(\frac{E_{oed,e}}{E_{oed,f}}\frac{l\,d}{s^2}\right) \tag{1}$$

where $\overline{k}$ is a parameter uniquely depending on the dilatancy angle of the embankment ($\overline{k}$ = 0.83 for dilatancy angle equal to zero); $E_{\mathrm{oed,e}}$ and $E_{\mathrm{oed,f}}$ are the oedometric moduli of the embankment and foundation soil, respectively. ϕ'_{ss} is the embankment friction angle in simple shear:

$$\tan\phi'_{ss} = \frac{\cos\psi_e \sin\phi'_e}{1 - \sin\psi_e \sin\phi'_e} \tag{2}$$

Equation 1 gives a conservative estimation of H^* in case of GRPSE (Mangraviti *et al.* 2022).

In the design practice, it is convenient (and strongly recommended by the current standards) to keep differential settlements at the top of the embankment in the r-direction (r defined in Figure 1b) negligible, by having an embankment higher than the critical height value ($u_{\mathrm{t,diff}} = 0$, if $h > h^*$). Under this conditions, differential settlements at the top of a GRPSE induced by the application of a distributed load Δq are always nil, regardless of the value of Δq (Figure 2). However, average settlements at long term ($u_{\mathrm{t,av}}$ in Figure 2) due to Δq are larger than zero (Mangraviti *et al.* 2023c) and need to be evaluated. In fact, also average settlements can be problematic when becoming differential settlements in the y-direction (y defined in Figure 1b). In this paper, average and differential settlements at the embankment top are defined as:

$$u_{t,av} = \frac{u_{t,f}\left(s^2 - d^2\right) + u_{t,p}d^2}{s^2} \quad \text{and} \quad u_{t,diff} = u_{t,f} - u_{t,p} \tag{3}$$

where:

$$u_{t,p} = \frac{2\pi \int_0^{d/2} u_t(r)\,dr}{\pi d^2/4} \quad \text{and} \quad u_{t,f} = \frac{2\pi \int_{d/2}^{s/2} u_t(r)\,dr}{\pi(s^2 - d^2)/4} \tag{4}$$

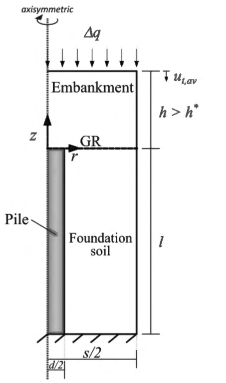

Figure 2. Problem geometry.

are the weighted average values of u_t above the pile ($0 < r < d/2$) and the foundation soil ($d/2 < r < s/2$), respectively. u_t are the vertical displacements accumulated during construction at the top of the embankment.

In engineering practice, engineers might be requested to design GRPSE in a way that settlements at the top of the embankment would be less than an admissible value ($u_{t,av}^{amm}$). By assuming that the increment of average settlement induced by Δq is equal to the value of $u_{t,av}^{amm}$ for the project, the efficiency of GRPSE in terms of settlements can be defined as:

$$efficiency = 1 - \frac{u_{t,av}^{amm}}{u^*} \tag{5}$$

where u^* is the increment of average settlements at the top of the embankment that would be induced by Δq if nor piles neither GR were installed:

$$u^* = q\left(\frac{l}{E_{oed,f}} + \frac{h}{E_{oed,e}}\right). \tag{6}$$

Usually, $h/E_{oed,e} \to 0$ since the embankment soil is very stiff.

Mangraviti (2022) used the meta-model by Mangraviti *et al.* (2022, 2023a) to define efficiency isolines in the s/d – $(Jl)/(E_{oed,f}\, d^2)$ non-dimensional plane (Figure 3). The plot reported in Figure 3 refers to friction angle and dilatancy angle of the embankment equal to $\phi'_e = 40°$ and $\psi_e = 0$, respectively. During a preliminary design stage, efficiency isolines can be a very effective tool to optimize pile spacing (s) and GR stiffness (J) considering the required

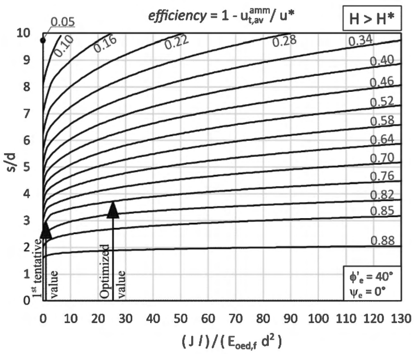

Figure 3. Mangraviti (2022): non-dimensional efficiency isolines for H (= h/d) > H^* (= h^*/d), $\phi'_e = 40°$ and $\psi_e = 0$.

average settlement at the top ($u_{t,av}^{amm}$). In fact, by calculating the efficiency (Eqs. 5,6), one isoline is individuated in Figure 3 and, knowing the mechanical properties of the foundation soil ($E_{oed,f}$) and its thickness (l), the value of s and J can be chosen in order to get the larger value of pile spacing to reduce the number of concrete piles.

3 RESULTS

The case from Feng *et al.* (2017) of a GRPSE, with h = 5 m and built for 3.5 km of linear infrastructure, is here considered. The homogeneous foundation soil deposit of thickness l = 16 m has mechanical properties chosen as average values from Feng *et al.* (2017) (Table 1). A conservative estimation of GRPSE response is obtained by considering cohesionless soils.

Table 1. Materials mechanical properties for GRPSE.

	Unit weight kN/m^3	Young modulus MPa	Poisson ratio -	Oedometric modulus MPa	Friction angle °	Cohesion kPa	Dilatancy angle °
Foundation soil	19.2	10.2	0.3	13.69	24	0	0
Embankment soil	18	40	0.3	53.85	40	0	0

A uniformly distributed vertical load Δq = 12.5 kPa is applied at the top of the embankment (Figure 2) and the resulting admissible settlement at the top of the embankment is 3.5 mm.

The piles have d = 0.5 m, whereas the spacing needs to be designed together with the stiffness of the GR. The procedure previously described to optimize the design of GRPSE is here used to increase s and J in order to improve the sustainability of the project.

To identify the isoline corresponding to this case, the $efficiency = 1 - 0.0035/(12.5 \times 16/13690) = 0.76$ (Eq. 5) is calculated. A first tentative value of J is chosen (Table 2) and, by entering the plot in Figure 3 with $Jl/\left(E_{oed,f}d^2\right) = 120 \times 16/\left(13690 \times 0.5^2\right) = 0.6$ value, a pile spacing of s = 1.4 m is found on the isoline of $efficiency = 0.76$. Knowing s, the value of critical height is calculated (Eq. 1) to verify that $h^*(= 1.4m) > h(= 5m)$. The same procedure is used for one higher value of J ("optimized value" in Table 2), and the number of piles needed in the central part of the embankment along 3.5 km in this case results in 658 piles less than the first tentative case.

To calculate the tons of CO_2 saved by choosing the optimized option, an average value of EC (generally measured in mass of CO_2 emitted per mass of material) of concrete is considered (Table 3). Knowing the mass of concrete needed for each pile (7.9 t) and the tons of

Table 2. Optimizing the preliminary design of GRPSE.

	GR axial stiffness, J kN/m	Pile spacing, s m	Number of piles in 3.5 km –
First tentative value	120	1.4	2501
Optimized value	5000	1.9	1843

Table 3. Reinforced concrete mass and EC.

	Embodied Carbon, EC tCO_2/t	Mass kg/m^2
Concrete	1.08 (Koerner 2019)	2500

CO_2 emitted for each pile (1.08 $tCO_2/t \times 7.9$ t = 8.5 tCO_2), the total amount of CO_2 saved by reducing the number of piles is calculated (8.5 $tCO_2 \times 658 = 5580$ tCO_2).

4 CONCLUSIONS

In this paper, an innovative and simplified displacement-based method to design Geosynthetic-Reinforced and Pile-Supported Embankments in a preliminary stage was presented. The methodology was applied to a practical example, where two different configurations of pile spacing and stiffness of the geosynthetic reinforcement were considered. The mass of CO_2 emitted was calculated for both the cases, and the optimized design led to reducing the number of piles needed in the project, by reducing the mass of CO_2 emitted (related to concrete piles) of 26%.

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