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Basal reinforced earth embankments on piled foundations: The role of embankment construction process

V. Mangraviti
Chalmers University of Technology, Gothenburg, Sweden

L. Flessati
Delft University of Technology, Delft, The Netherlands

C. di Prisco
Politecnico di Milano, Milan, Italy

ABSTRACT: The current design methods for Geosynthetic-Reinforced and Pile-Supported embankments disregard on one side the effect of the embankment construction and on the other one the stiffness of embankment, foundation soil, column and geosynthetics. What is missing nowadays is a simplified design method capable of taking all these aspects into account. To this aim, in this paper the authors present the results of a series of numerical analyses simulating the embankment construction. In particular, the evolution during construction of embankment displacements is discussed and the maximum tensile force in the geosynthetic reinforcements is compared with the one suggested by the most popular standards. To clearly highlight the mechanical processes taking place in the embankment, an ideal problem is considered: the pile shaft is assumed to be smooth, the piles to be founded on a rigid bedrock and the embankment construction to take place under drained conditions.

1 INTRODUCTION

Piled foundations are commonly employed to reduce settlements of artificial earth embankments on soft soil strata, and geosynthetic reinforcements are installed at the embankment base to increase pile spacing, that is to reduce construction costs. Despite the well documented effectiveness of this technique, the mechanical processes developing during the construction are not fully understood and the current design approaches, based on very simplified assumptions, ignore them.

In the scientific literature, the problem is usually tackled in the light of Ultimate Limit State (ULS) theory and the mechanical response of Geosynthetic-Reinforced Pile-Supported (GRPS) embankments, that is the vertical stress transfer to piles (arching effect) and the arising of the plane of equal settlements (plane above which differential settlements are negligible), is interpreted by assimilating it to the trapdoor problem. Nevertheless, experimental data (Iglesia 1991; Reshma *et al.* 2020; Terzaghi 1936) have shown that (i) the arching effect is strongly affected by both geometry and embankment mechanical properties, and (ii) the stresses acting on the foundation soil significantly depend on the differential displacements imposed at the base. All these observations put in evidence the crucial role played by the material deformability and, therefore, the unsuitability of trapdoor-based approaches to investigate the serviceability conditions of GRPS embankments (Mangraviti 2022; Mangraviti *et al.* 2022a).

Therefore, in the last decades, numerical studies, considering the presence of the foundation soft soil stratum (absent in the trapdoor geometry), were performed by using either finite element or finite difference (Flessati *et al.* 2022; Han & Gabr 2002; Mangraviti *et al.* 2022b; Stewart &

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Filz 2005) codes or both (Jennings & Naughton 2012). It worth mentioning that in general these studies (i) do not focus on the effects of the embankment construction, (ii) do not take large displacements into account and (iii), thus, disregard the membranal behavior of geosynthetics.

In this paper, the authors discuss the results of a series of finite difference numerical analyses simulating the construction of the embankment under drained conditions, by accounting for the membranal mechanical behavior of the geosynthetic layer. Since the final goal of this research is to conceive a simplified mathematical "meta-model" to evaluate settlements at the top of the embankment during construction, the problem considered here in the following is ideal: (i) a unit axisymmetric cell of the embankment is analyzed (boundary effects are not accounted for), (ii) the pile shaft is assumed to be smooth and (iii) the pile are assumed to rich a rigid underneath bedrock.

The paper is structured as it follows: in §2 the numerical model is described; in §3 the results in terms of maximum tensile force and settlements at the top of the embankment are discussed and in §4 what learnt is briefly summarized.

2 NUMERICAL MODEL

In this paper, the authors considered the effects of embankment construction on the central part of GRPS embankments. Therefore, the problem schematized in Figure 1a (where z is the vertical coordinate) is reduced to the analysis of one central axisymmetric cell (Figure 1b, where r is the radial coordinate). The unit cell of diameter s, assumed to be equal to the pile spacing (to each pile disposition a suitable definition for the unit cell diameter has to be assigned) includes: (i) the pile of diameter d and length l, (ii) a homogeneous foundation soil stratum of thickness l resting on a rigid bedrock, (iii) an embankment, whose height h evolves during the construction phase and (iv) the geosynthetic reinforcement laid at the embankment base. As previously mentioned, the pile shaft is assumed to be smooth and the construction process to take place under drained conditions.

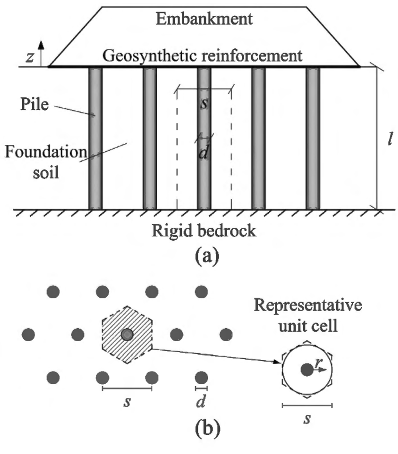

Figure 1. (a) Problem geometry in transversal section; (b) Pile disposition in plan and representative axisymmetric unit cell.

The unit cell of Figure 1b has been modelled as illustrated in Figure 2. The numerical problem has been solved by using a finite difference numerical code (FLAC3D 6.0, Itasca 2017). A large displacement approach has been used and the spatial discretization has been optimized by choosing smaller elements close to the pile, where strains are expected to localize.

Normal displacements are not allowed along both the lateral boundaries and the bottom of the model. The pile is assumed to be elastic and, analogously to what done by many authors in the literature, the soil has been modelled by means of a non-associated elastic-perfectly plastic constitutive relationship with a Mohr-Coulomb failure criterion. This constitutive relationship, despite of its simplicity, can capture the main aspects of the mechanical processes taking place in the considered spatial domain (Mangraviti *et al.* 2022c). The geosynthetic reinforcement has been modelled as an elastic isotropic membrane of axial tensile stiffness J.

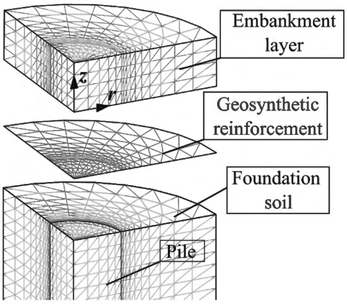

Figure 2. FLAC3D numerical model layout and spatial discretization.

Between pile and foundation soil, smooth interface elements are inserted. Along normal direction, under compression, the interface elements are "quasi rigid" (the elastic stiffness is sufficiently larger than the soil one, equal to 4e5 kN/m^3), whereas under tension perfectly fragile. Between the geosynthetic and the surrounding soil, frictional interface elements quasi-rigid along the normal direction are introduced. The interface friction angle is imposed to coincide with that of the soil (in agreement with the experimental findings by Moraci *et al.* (2014)).

The layer-by-layer embankment construction is subdivided in single stages, each one corresponding with the deposition of 0.25 m of granular material (for the sake of simplicity, both pile installation and soil compaction are not reproduced). At each construction stage, a new stratum of elements is added on the current position of the embankment top. This allows to reproduce, in contrast with what done by Han & Gabr (2002) and Jennings & Naughton (2012), although in a simplified way, the real loading path followed by the system during the embankment construction.

To study the mechanical processes taking place during the embankment construction, a parametric study, in which different geometries and mechanical properties have been considered, was performed. The results differ from a quantitative point of view but are qualitatively consistent. As a consequence, for the sake of brevity, the numerical results will be discussed here in the following by considering only a reference case of fixed geometry (s = 1.5 m, d = 0.5 m, l = 5 m) and given mechanical properties of materials (Table 1).

Table 1. Mechanical properties of the materials for the reference case.

	Unit weight kN/m^3	Young modulus MPa	Poisson ratio -	Friction angle °	Cohesion kPa	Dilatancy angle °	J kN/m
Foundation soil	18	1	0.3	30	0	0	-
Embankment	18	10	0.3	40	0	0	-
Pile	25	30000	0.3	-	-	-	-
Geosynthetic reinforcement	-	-	0.3	-	-	-	1000

3 RESULTS AND DISCUSSION

Analogously to what already observed by Han & Gabr (2002), the distribution of the total tensile force per unit thickness within the geosynthetic is not uniform and varies along the radial coordinate (Figure 3a). In this figure, the tensile stress is integrated along the current circumference, reducing with *r*. For this reason, although the tensile stress is maximum at the pile edge, the tensile force has a maximum for $r = 0.3$ m. The numerical results from this study (Figure 3a, solid line) are compared with the value of maximum tensile force assessed (for the reference case and $h = 5$ m) by according to what suggested by one of the most popular standard in the field (BS8006-1 2010), that assumes an unrealistic uniform distribution of tensile force in the geosynthetic (Figure 3a, dotted line).

The values of the maximum tensile force calculated for different values of *h* by using BS8006-1 (2010) were found to be always larger than the ones obtained in this study (Figure 3b). This result is consistent with the hypothesis at the base of the standards. In fact, as was already observed by Bhasi & Rajagopal (2015), ULS approaches lead to an extremely conservative estimation of the maximum tensile force in the geosynthetic.

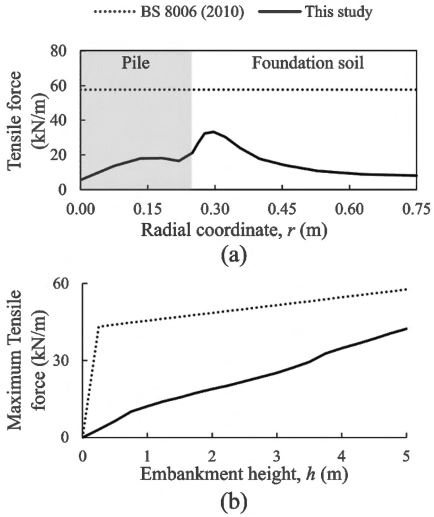

Figure 3. Comparison between numerical analyses from this study and BS8006 (2010) for the reference case: (a) Tensile force within the geosynthetic along the radial coordinate for $h = 5$ m; (b) Maximum tensile force of the geosynthetic reinforcement calculated for different values of *h*.

To better understand the mechanical behavior of GRPS embankments, the evolution of irreversible deviatoric strain contours during construction was analyzed: Figures 4 a-c refer to three representative values of *h*. The results show that deviatoric strains localize in a cylindrical crown (defined as "process zone", in agreement with what suggested by (di Prisco *et al.* 2020a, 2020b) close to the pile edge, while in the rest of the spatial domain deviatoric strains are negligible. For small *h* values, the height of the process zone (h_p) coincides with the embankment height, but, when the embankment height gets a threshold value ($h_p = h^* = 1.1$ m, for the reference case), h_p stops evolving. As a result of the parametric study, it was found that h^* is a function of: (i) geometry (*s*, *d* and *l*); (ii) embankment soil friction and dilatancy angle; (iii) relative stiffness between pile, foundation soil and embankment soil and (iv) *J*.

As in Mangraviti *et al.* (2022b), the numerical results in terms of average and differential settlements at the top of the embankment have been plotted (Figure 5). Average ($u_{t,av}$) and differential ($u_{t,diff}$) settlements at the embankment top are calculated as:

$$u_{t,av} = \frac{u_{t,f}\left(s^2 - d^2\right) + u_{t,p}d^2}{s^2} \text{ and } u_{t,diff} = u_{t,f} - u_{t,p} \quad (1)$$

where:

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

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

Once the height of the embankment becomes larger than h^*, differential settlements stop increasing, regardless of the final height of the embankment (Figure 5). h^* can also be interpreted as a "critical height" and is analogous to the height of the plane of equal settlements observed by Terzaghi (1936) and Han & Gabr (2002).

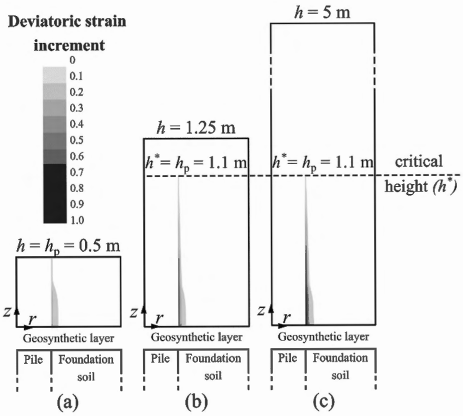

Figure 4. Contour of deviatoric strains in the embankment during construction for the reference case and evolution of process height, h_p, for three representative h values: (a) h = 0.5 m; (b) h = 1.25 m; (c) h = 5 m.

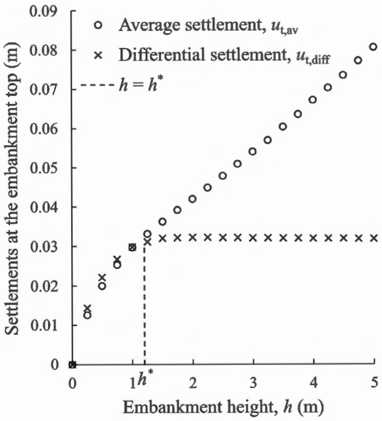

Figure 5. Average and differential settlements at the top of the embankment during construction for the reference case.

4 CONCLUSIONS

In this paper, the results of a finite difference numerical analysis campaign, modelling an ideal axisymmetric unit cell of Geosynthetic-Reinforced and Pile-Supported embankments are discussed. For the sake of brevity, only the results concerning a reference case are illustrated. The results, in terms of both maximum tensile force in the membrane and settlements at the top of the embankment during drained construction of the embankment have been discussed. In particular, the numerical results highlighted the importance of taking into consideration the stiffness of the materials involved for a reliable estimation of the critical embankment height. Furthermore, the authors emphasized the importance of considering the layer-by-layer embankment construction to properly reproduce the mechanical processes progressively developing within the embankment and, therefore, to correctly estimate: (i) the tensile force acting in the membrane and (ii) average and differential settlements at the top of the embankment.

According to the authors, the very conservative approach of current design methods, based on ultimate limit state theory and not accounting for staged construction processes, lead to a significative overestimation of the force acting in the membrane. This does not allow for an adequate optimized and sustainable design of GRPS embankments from a serviceability limit state perspective.

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