Modelling the Development of Settlements of Earth Embankments on Piled Foundations

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Abstract. In the design of earth embankments on soft soil strata, piles are often employed as settlements reducers. Despite of their well-documented effectiveness, the complex interaction processes transferring loads to piles within both the embankment and the soft foundation soil, are not yet totally understood. As it is well known, the effectiveness of this intervention is strictly related to the construction rate. In fact, the consolidation process taking place in the foundation soil induces the accumulation of settlements with time. The settlements increment at the embankment base, induces stresses migration towards the pile.

In this paper, the results of an extensive numerical campaign performed by using a 3D finite difference code are presented. The numerical model allows to calculate the differential settlements at the top of the embankment and to appreciate the effects of both the consolidation and the construction processes.

Keywords: Piled embankments · Construction process · Hydro-mechanical coupling · Finite difference numerical analysis

1 Introduction

Engineering design methods, generally based on simplified approaches, do not allow to quantitatively evaluate total and differential settlements at the top of embankments both during and after the construction. Due to the employment of piles, complex stress transferring mechanisms take place. In particular, (i) vertical stresses migrate toward the piles within the embankment; (ii) tangential stresses are transferred to the top of the pile, leading to a decrease in the stresses applied to the soft soil stratum and (iii) plastic strains develop within the embankment. These soil-structure interaction mechanisms are governed by both the geometry and the relative stiffness of the elements constituting the system i.e. piles, foundation soil and embankment soil.

The approaches suggested in the most used design standards (EBGEO 2010; BS8006-1 2010; ASIRI 2012) to analyze the response of this type of "geo-structures", based on the concept of arching effect (Marston and Anderson 1913; Terzaghi 1943; Van Eeckelen 2013), allow to estimate the stresses applied to the pile and neglect the embankment settlements.

In contrast, the design of infrastructures, such as railways or highways, is nowadays inspired to displacement-based approaches. To this aim, the evaluation of differential settlements at the top of the embankment is crucial (di Prisco et al. 2019) to both

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optimize the use of materials and reduce the construction cost (Flessati 2020). In this framework, the concept of plane of equal settlements (Terzaghi 1943; McKelvey 1994; Naughton 2007; McGuire 2011; di Prisco et al. 2019) has, according to the authors, to be reinterpreted since it allows to capture the capability of embankment soils of redistributing stresses.

In this paper, this concept is employed to theoretically interpret the results of a series of 3D nonlinear finite difference numerical analyses. In particular, the effect of the construction rate of the embankment is considered and, for the sake of brevity, only two different cases will be compared: the drained (very slow construction rate) and undrained (very high construction rate) cases. The evolution in time of the plane of equal settlements is critically discussed.

2 Numerical Model

The geometry of the system here considered is shown in Fig. 1a. In order to disregard flank effects, only one axisymmetric cylindrical cell has been considered (Fig. 1b). The cell is composed of: (i) one pile of diameter d and length l, (ii) surrounding soil and (iii) embankment stratum h thick. The diameter of the whole cell s is assumed to coincide with the pile spacing. On the lateral boundaries of the domain normal displacements are not allowed. At the base of the axisymmetric cell nil displacements are imposed. The concrete pile is modelled as a linear elastic cylindrical inclusion. The mechanical behaviour of both the foundation and the embankment soil is assumed to be elastic-perfectly plastic. The failure condition is given by the Mohr-Coulomb criterion and the flow rule is assumed to be non-associated. Smooth interface elements are introduced between pile and foundation soil.

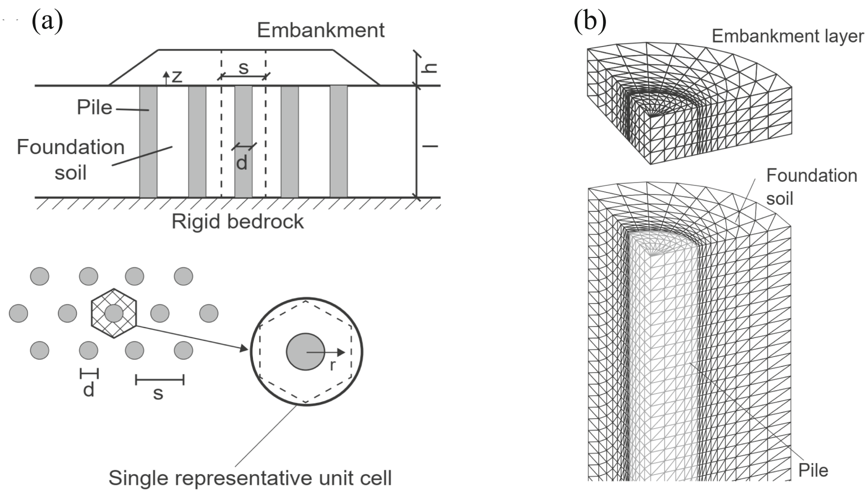

Fig. 1. (a) Geometry of the problem; (b) numerical discretization of the problem.

For the sake of brevity, the results presented here below refers to one fixed geometry (Table 1) and to one set of mechanical parameters (Table 2).

Table 1. Geometrical parameters

h (m)	l (m)	s (m)	d (m)
5.0	5.0	1.5	0.5

Table 2. Mechanical parameters

Material	Unit weight (kN/m^3)	Young modulus (MPa)	Poisson's ratio (-)	Friction angle (°)	Dilatancy angle (°)
Foundation soil	18	1	0.3	30	0
Embankment	18	10	0.3	40	0
Column	25	30000	0.3	–	–

2.1 Drained Case

If the construction rate is significantly larger than the consolidation rate, the hydromechanical coupling can be disregarded and the embankment construction takes places under drained condition. In this case, all the variables can be plotted against the current embankment high h. In this model, the embankment layers are 25 cm high. The numerical results are here below illustrated in terms of:

- the average values of the vertical stresses (σ_v) acting at the top of the pile and on the foundation soil at the base of the embankment $z = 0$ m (Fig. 2a);
- the differential settlements (u_{diff}) at the top and the base of the embankment.

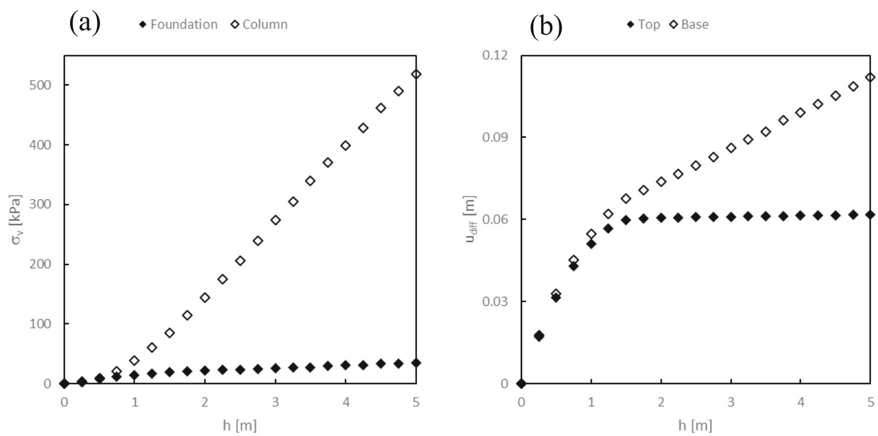

Fig. 2. Construction process: (a) vertical stresses at the base of the embankment acting on the column and on the foundation soil; (b) differential displacements at the top and at the base of the embankment.

In Fig. 2a it can be noticed that during the first steps of the construction (low values of h) the stresses acting on the column are equal to the ones acting on the foundation soil. After a certain value of h (approximately 0.5 m) the embankment becomes thick enough and the two stresses markedly differ. Analogously, differential settlements at the base and at the top initially coincide ($h < 0.5$ m), but in the following ($h > 1.5$ m) the differential settlements at the top get an asymptotic value whereas the differential settlements at the base linearly and monotonically increase. Such a behaviour can be justified by introducing the concept of process height h_p describing the height of the localized zone where plastic strains progressively develop (Fig. 3). Until $h = h_p$, u_{diff} at the top coincide with u_{diff} at the base. When the distortional strains stop evolving, u_{diff} at the top stops evolving as well, whereas u_{diff} at the base does not stop to increase. This implies that the embankment exhibits a plastic behaviour only at the beginning of the construction, becoming elastic-plastic when $h > h_p$.

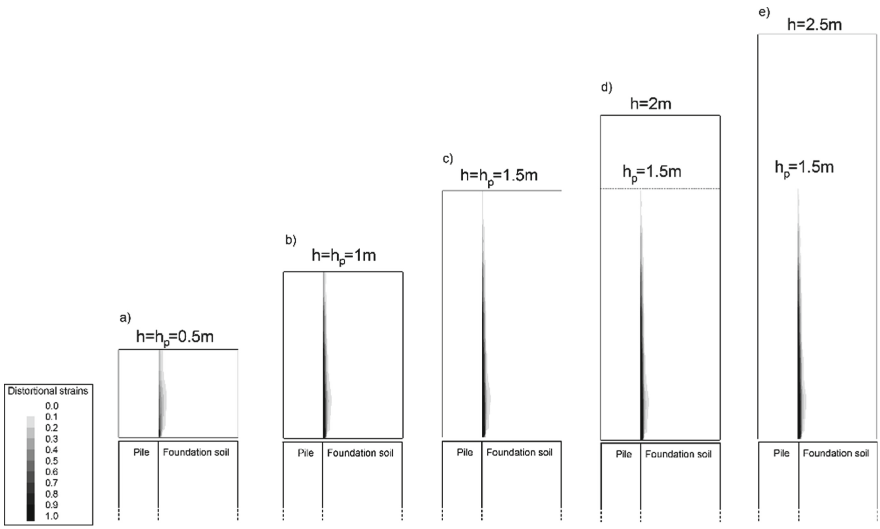

Fig. 3. Process height (h_p) evolution during the construction process.

2.2 Undrained Case

In this case the construction process takes places under undrained conditions i.e. after the construction of the embankment settlements are almost nil (since foundation soil does not accumulate any vertical strain). All the settlements are expected to develop with time after the construction when the consolidation of the foundation soil takes place (water table in $z = 0$ m). In this case, to describe the response of the system, the height of the embankment is kept constant during the consolidation process.

Vertical stresses acting on the top of the column and on the foundation soil for $z = 0$ m (Fig. 4a) start with the same value (the weight of the embankment). With time the vertical stresses on the column progressively increase whereas the vertical stresses

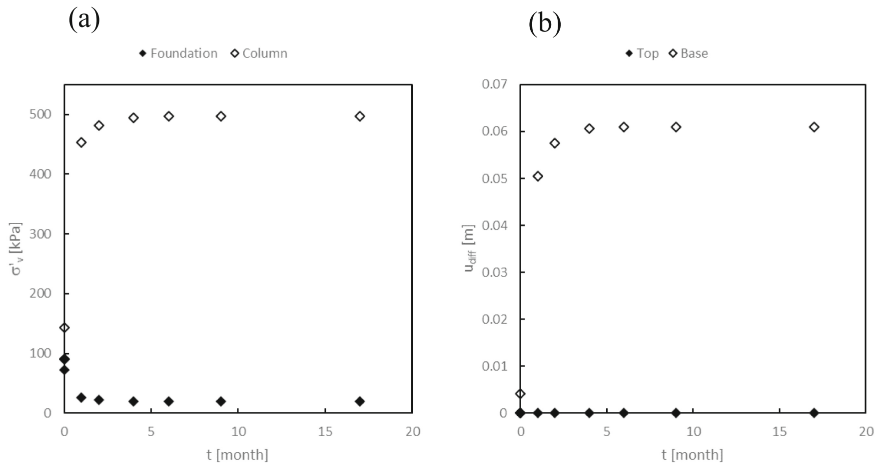

Fig. 4. Consolidation process: (a) vertical stresses at the base of the embankment acting on the column and on the foundation soil; (b) differential displacements at the top and at the base of the embankment.

on the foundation soil progressively decrease. Analogously, the differential settlements at the base increase with time although the total vertical stresses applied on the foundation soil are decreasing. When the pore water pressure starts reducing, the plane of equal settlements starts moving upwards (Fig. 5). Since $h_p < h$ for any instant of time no differential settlements are induced at the top of the embankment (Fig. 4b).

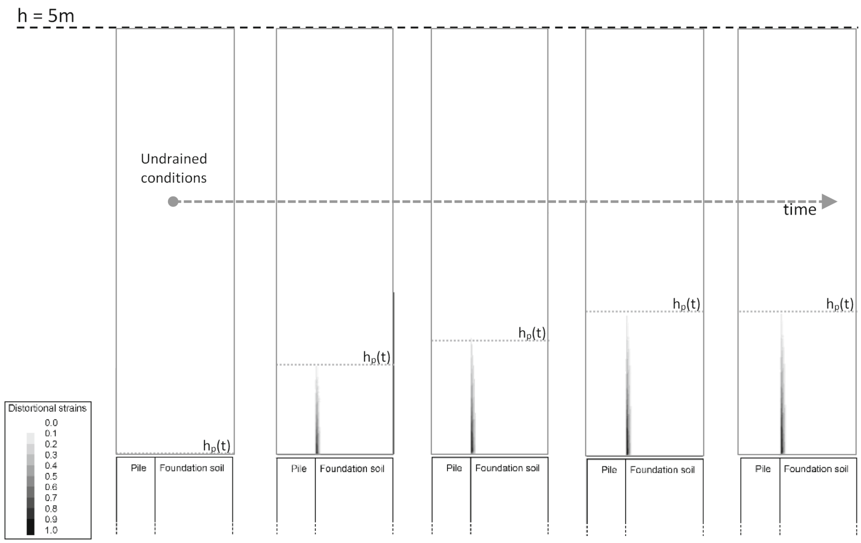

Fig. 5. Process height (h_p) evolution during the construction process

In contrast to what observed in the previous paragraph for the drained case (Sect. 2.1), in this case the embankment starts behaving elastically and with time evolves toward a plastic regime.

3 Discussion and Conclusions

In the present study, a series of numerical analysis taking into account the construction rate of the embankment on pile foundations has been carried out. For the sake of brevity, two extreme case have been illustrated: very high and very low construction rates. Although the two numerical models are characterized by the same geometrical and mechanical parameters, the response of the two cases is profoundly different. By comparing the obtained results, it is worth noting that the differential settlements at the top of the embankment reduce by either reducing the construction time or increasing the consolidation time. On the contrary, the final values of stresses applied to the column are not significantly affected by the consolidation process.

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