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A two-phase model and related numerical tool for the design of soil structures reinforced by stiff linear inclusions

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Abstract

A two-phase macroscopic model is presented for ascertaining the overall linear elastic behaviour of a soil reinforced by stiff long inclusions, with a particular emphasis on the shear and flexural behaviour of the reinforcements. Based on a minimum principle for the potential energy of any two-phase system, expressed as a function of the kinematically admissible displacement and rotation fields, a finite element formulation is established, resulting in the elaboration of a numerical computer code devoted to the simulation of any reinforced soil structure under plane strain conditions. This finite element code is applied to the evaluation of the settlements experienced by a rigid raft foundation placed on top of a soil reinforced by a group of vertical piles, and subject to combined loading conditions. One of the important conclusions which may be drawn from such a quantitative analysis is that the shear and flexural behaviour of the reinforcing piles, as well as the way these piles are connected to the foundation, play a decisive role in the case of lateral loading.

Keywords: Reinforced soils; Stiff inclusions; Shear and bending effects; Multiphase model; Finite element method; Piled raft foundations

1. Introduction

Fibre composite materials, as well as soils reinforced by linear inclusions or even rubber bearings strengthened by steel plates, provide typical examples, at quite different scales, of a homogeneous matrix-material reinforced by one or several arrays of long continuous inclusions placed along preferential directions. The strong heterogeneity, combined with the high number of reinforcements involved in structures elaborated with this kind of materials, makes it difficult, if not impossible, to devise appropriate analysis and design methods in which the inclusions could be dealt with as individual elements. Therefore, alternative methods based upon constitutive models aimed at capturing the macroscopic behaviour of this kind of materials, could possibly overcome such difficulties. While, as a matter of fact, there is no real other alternative as far as fibre composite materials are concerned, the idea of homogenisation appears to be a rather innovative concept in the field of inclusion-reinforced geotechnical structures.

A so-called "multiphase model" has been recently proposed (de Buhan and Sudret, 2000a; Sudret and de Buhan, 2001; Bennis and de Buhan, 2003) which provides a mechanically consistent framework to set up appropriate design methods for

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these structures, with a dramatically reduced computational effort, compared to that required when trying to perform numerical simulations directly. For many applications, a simplified version of this model, where the reinforcements could be considered as "flexible", that is working as tensile load carrying structural elements (reinforced earth embankments or even soil nailed slopes and rock bolted tunnels), appears to be fully adequate. On the other hand, as regards soil structures reinforced by "stiff" linear inclusions (example of piled raft foundations), such a simplified model may prove unduly conservative, in that it does not account for the shear and bending stiffness of the reinforcements, which could be expected to play a decisive role in some particular situations, such as in the case of a foundation subject to seismically induced lateral loading.

Predicting the settlements of shallow foundations on a soil reinforced by a group of vertical inclusions (metal or concrete piles) remains a difficult challenge due to the complex interactions prevailing between the reinforcements and the surrounding soil, more particularly as soon as a relative large number of inclusions is involved. Several attempts have been made for instance to develop appropriate numerical methods, such as the well-known "hybrid model" (Chow, 1986; Griffiths et al., 1991; Clancy and Randolph, 1993). This model is based on a discretization of the reinforcing piles into one-dimensional rod elements, the interaction between these reinforcements and the surrounding soil mass being taken into account by means of springs allowing to describe the shear forces acting at the pile/soil interface. An intensive use of the Mindlin solution giving the displacement field of an elastic half-space under pin point load is made, in order to specify the interaction between the reinforcements through the soil mass. One of the major limitations of this "hybrid model", apart from being based upon the assumption of linear elastic behaviour, lies in the fact that it is restricted to pure vertical loadings.

A fully three-dimensional simulation of this kind of structure has been carried out by Vetter (1998), by means of the finite element computer code ABAQUS, using 8-node isoparametric elements for discretising both the soil and the piles, separately, leading to a mesh comprising several thousands elements. The results of such a simulation expressed in terms of a global load-settlement curve have been favourably compared with in situ measurements made on the actually built structure. Implementing the simplified version of the above mentioned "multiphase model", Sudret and de Buhan (2001) have shown that the computational time needed for performing this kind of calculations could be divided by as much as several hundreds, thus making it possible to conduct parametric studies where the number of piles, as well as their mutual spacing, length or diameter, could be varied, without it being necessary to change the mesh of the structure.

The main limitation of the simplified "multiphase model" may be overcome by developing a generalized model in which, referring to the beam-like characteristics of the reinforcements, their shear and flexural components, and not only their axial component, are incorporated in the analysis. This leads to the description of the reinforcement phase as an oriented micropolar continuous medium, in much the same way as that proposed for layered materials (Adhikary and Dyskin, 1997) or cellular solids modelled as beam lattices (Askar and Cakmak, 1968; Chen et al., 1998). As it has been recently shown (de Buhan and Sudret, 2000b), the main advantage of the proposed multiphase model as compared with a classical homogenisation procedure, lies in its ability to capture and quantify a "scale effect" which may be attributed to the reinforcement flexural behaviour. This means for instance, from a practical point of view, that the reinforcing capacity of a group of N piles of diameter d, is greater than that which could be expected from a group de $4N$ piles of diameter equal to $d/2$.

This paper is more specifically concerned with the development of the generalized multiphase model towards the elaboration of an attractive computational tool for simulating the behaviour of soil structures reinforced by stiff linear inclusions, such as piled raft foundations. The principal characteristics of the multiphase model are first recalled in Section 2, in the particular case of a soil reinforced by one single array of inclusions placed along the same direction. The equilibrium along with the constitutive equations of the corresponding two-phase model are detailed in the situation of plane strain linear elasticity. This model is then applied in Section 3, for deriving the analytical solution relative to the problem of a reinforced layer subject to transverse shear loading. The analysis is more particularly focused on assessing the influence of the reinforcements shear deformability. Section 4 is then devoted to the general statement of an elastic boundary value problem for a two-phase system, the formulation of a minimum principle for the potential energy, and to the presentation of a numerical implementation of this principle within the context of the finite element method. Finally, the finite element code developed on such guidelines, is applied in Sections 5–7 to the simulation of the global behaviour of a piled raft foundation subject to combined loading.

2. A two-phase model for soils reinforced by stiff linear inclusions

The subsequent developments are restricted to the case when the soil, which is assumed to be reinforced by one single array of evenly distributed parallel linear inclusions placed along the Ox-axis, is subject to plane-strain loading conditions in the Oxy-plane, as shown in Fig. 1(a), which provides a description of the reinforced soil at the microscopic scale as a periodic composite material. According to the two-phase model developed by de Buhan and Sudret (2000a) in the general three-dimensional case, the composite reinforced soil may be regarded at the macroscopic scale as the superposition of two 2D continuous media, called *matrix* and *reinforcement phases*, respectively. It notably means that matrix and reinforcement particles are geometrically coincident at any point (x, y), as shown in Fig. 1(b). Furthermore, each particle is given its own