Computers and Geotechnics 100 (2018) 15–29

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Numerical simulation of two-tier geosynthetic-reinforced-soil walls using two-phase approach

Ehsan Seyedi Hosseininia[a,*], Ahoo Ashjaee[b]

[a] Civil Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Iran
[b] Civil Engineering Department, Mazandaran Institute of Technology, Iran

ARTICLE INFO

Keywords:
Reinforced soil
Two-tier walls
Two-phase model
Numerical simulation
Deformation
Performance

ABSTRACT

In this study, the mechanical behavior of two-tier Geosynthetic-Reinforced Soil walls is investigated numerically by using the concept of two-phase systems. Comparison of the results of this approach with those of discrete numerical models and centrifuge tests indicates that the approach has the ability to consider the interaction between tiers, predict the reinforcement load and wall-face displacement. Furthermore, it is more cost-effective. The limitations of this approach pertain to the prediction of the failure surface and the wall deformation regime. Totally, the two-phase approach can be properly applied in a fast, effective and safe manner.

1. Introduction

Geosynthetic-Reinforced Soil (GRS) walls are now widely used in civil engineering practice. In some cases, GRS walls are designed and constructed in tier configurations rather than utilizing them as single walls due to wall stability, construction constraints, space requirements for drainage along the height of the wall, and aesthetics. The wall design with tier configuration is more complicated than a single wall since the upper and lower tiers mutually interact over wall deformation and reinforcement loads.

There are generally two approaches for design and analysis of multi-tier GRS walls. A lateral earth pressure method, which is based on an empirical extension of single-tier GRS walls, is introduced by the NCMA [1] and FHWA guidelines [2,3]. This method results in an overestimation of design requirements [4–8]. The limit equilibrium (LE) method whose applicability has been examined and approved in [4,5,9,10] is another approach. These two approaches are only yield wall stability and no information about wall deformation and reinforcement load distribution can be obtained. Thus, numerical analyses should be implemented in the design procedure.

Numerical methods have been widely used in order to study the performance of multi-tier GRS walls as well as the interactions between the tiers. Yoo and Song [11] performed plane-strain finite element simulation of two-tier GRS segmental retaining walls. The results indicate that an unexpected yield in the foundation may affect both internal and external stability of the lower tier owing to the absence of toe resistance. In addition, upper-tier reinforcement length has a significant influence on lower-tier lateral deformation. Yoo and Kim [12] calibrated a three-dimensional finite element (FE) model of a full-scale test wall to further investigate load carrying capacity and relevant performance of the test wall under surcharge load. Stuedlein et al. [9] simulated a four-tier 46-m-tall reinforced wall using the finite difference code FLAC. Although the overall design in this work was based on the LE method, they utilized numerical simulations in order to assess wall performance and predict wall displacements at times of soil liquefaction. Yoo et al. [8] carried out a series of finite element (FE) analyses in order to investigate internal stability of small-scale two-tier GRS walls with various offset distances and reinforcement distributions. They showed that the lower-tier reinforcement length has a greater effect on overall wall stability than the upper-tier reinforcement length. Recently, Mohamed et al. [6] compared the results of numerical simulations of two-tier GRS walls with those of a centrifuge modeling series which included different offset distances. They concluded that there is an excellent agreement for slip surfaces and reinforcement loads between the LE/FE methods and centrifuge tests. Generally, it can be said that in comparison with the LE method, numerical methods offer more comprehensive information about stress, strain, force, and displacement at any location of interest.

We can consider the reinforced soil medium as a composite which behaves, at the macroscopic level, as a homogenous but anisotropic composite material [e.g. 13–16] due to the existence of repeated layers of soil and reinforcing elements in a periodic manner. For reinforced soil medium, a new concept called the "Multiphase Model" has been introduced by de Buhan and Sudret [17] which is an extension of the

* Corresponding author.
E-mail addresses: eseyedi@um.ac.ir (E. Seyedi Hosseininia), ashjaee.a@gmail.com (A. Ashjaee).

https://doi.org/10.1016/j.compgeo.2018.04.003
Received 9 October 2017; Received in revised form 28 February 2018; Accepted 2 April 2018

classical homogenization technique. In this technique, the composite is represented at the macroscopic scale not by a single medium as in the homogenization methods, but by superposed mutually interacting media (or "phases"). Accordingly, reinforced soil can be regarded as a two-phase medium such that each geometrical point represents two coincident particles including matrix phase (representative of soil) and reinforcement phase (representative of inclusions). In general, it is possible to dedicate different kinematic fields to each phase relating to each other through an interaction law. Consequently, the multiphase model can capture both scale and boundary effects [18] contrary to classical homogenization methods. The two-phase model has been utilized in order to investigate the performance of single GRS walls under static [19–21] and dynamic loads [22].

The mechanical behavior of two-tier GRS walls is investigated by using the two-phase approach and numerical simulations in the present study. The numerical finite difference method is used in this work. The applicability of the two-phase approach to consider tiers interaction and the influence of gird size are investigated. The results are compared with those of centrifuge modeling performed by Mohamed et al. [5]. For simplicity, the Mohr-Coulomb model is selected for the soil constitutive model and a linear elastic perfectly-plastic model is considered for reinforcements. The discrete modeling approach is also utilized in this study to get a better understanding of the capability of the two-phase approach.

2. Reinforced soil as a two-phase material

Fig. 1 presents the concept of a two-phase material for reinforced soil. According to Fig. 1a, reinforced soil is a periodic medium in which reinforcement layers are placed in a systematic order among the soil medium. A two-phase system introduces a macroscopic description of a composite medium as superposition of two individual continuous media called phases. Each point of the geometry in a two-phase material consists of matrix phase that represents soil and reinforcement phase implying axial inclusions as shown in Fig. 1b. The two-phase concept has also been implemented to simulate the behavior of reinforced soil structures. In such structures, linear elements such as piles or bolts are installed in the soil in order to augment the bearing capacity or reduce the deformations of the soil medium. Examples of two-phase problems of reinforced soil structures are using bolts in tunneling [23,24], piled rafts [25–27], and piled embankments [28].

In a two-phase material, each phase has its own specific characteristics similar to what is defined for each constituent in discrete form. Based on the theory of the virtual work method, the equilibrium equation for each phase is defined separately as follows [17,29]:

$$div\boldsymbol{\sigma}^m + \rho^m\mathbf{F}^m + \mathbf{I} = \mathbf{0} \tag{1}$$

for the matrix phase, and

$$div\boldsymbol{\sigma}^r + \rho^r\mathbf{F}^r - \mathbf{I} = \mathbf{0} \tag{2}$$

for the reinforcement phase. The bold face letters in the equations are denoted as tensors and vectors. In the above equations, the superscripts m and r correspond to the matrix and reinforcement phases, respectively. $\boldsymbol{\sigma}$ denotes the stress tensor of each phase. The term $\rho\mathbf{F}$ indicates the external (body) force vector applied to the phases and $\mathbf{I}$ represents the interaction force vector mutually exerted from the phases. These equilibrium equations will be completed by the corresponding stress boundary conditions that are prescribed on the boundary surface of each phase separately.

The summation in Eqs. (1) and (2) gives the global equilibrium equation of a two-phase material in the following form

$$div\sum + \rho\mathbf{F} = \mathbf{0} \tag{3}$$

where

$$\sum = \boldsymbol{\sigma}^m + \boldsymbol{\sigma}^r, \quad \rho\mathbf{F} = \rho\mathbf{F}^m + \rho\mathbf{F}^r \tag{4}$$

$\sum$ represents the global stress tensor of a two-phase material which is the sum of partial stresses of both phases. Similarly, $\rho\mathbf{F}$ indicates the global body force of the two-phase material.

In a two-phase material, each phase has its own domain of kinematics which are defined by strain tensors $\boldsymbol{\varepsilon}^m$ and $\boldsymbol{\varepsilon}^r$ for matrix and reinforcement phases, respectively. For each phase, the stress-strain relationship is introduced individually:

$$\boldsymbol{\sigma}^m = \mathbf{D}^m\boldsymbol{\varepsilon}^m, \quad \boldsymbol{\sigma}^r = \mathbf{D}^r\boldsymbol{\varepsilon}^r \tag{5}$$

where $\mathbf{D}^m$(or $\mathbf{D}^r$) denotes the stiffness tensor of the matrix (or reinforcement) phase. The interaction body force $\mathbf{I}$ in Eqs. (1) and (2) can be defined as a function of relative displacement between phases [e.g. 20, 30, 31]. In the case of perfect bonding between phases, the kinematics of the phases become identical:

$$\in = \boldsymbol{\varepsilon}^m = \boldsymbol{\varepsilon}^r \tag{6}$$

where $\in$ denotes the strain tensor of the whole medium.

By considering Eqs. (4) and (6), the global stress-strain relationship of a two-phase material in the case of perfect bonding has the following tensor form:

$$\boldsymbol{\Sigma} = \mathbf{D}\in \tag{7}$$

where $\mathbf{D} = \mathbf{D}^m + \mathbf{D}^r$ and indicates the global stiffness tensor of the two-phase material.

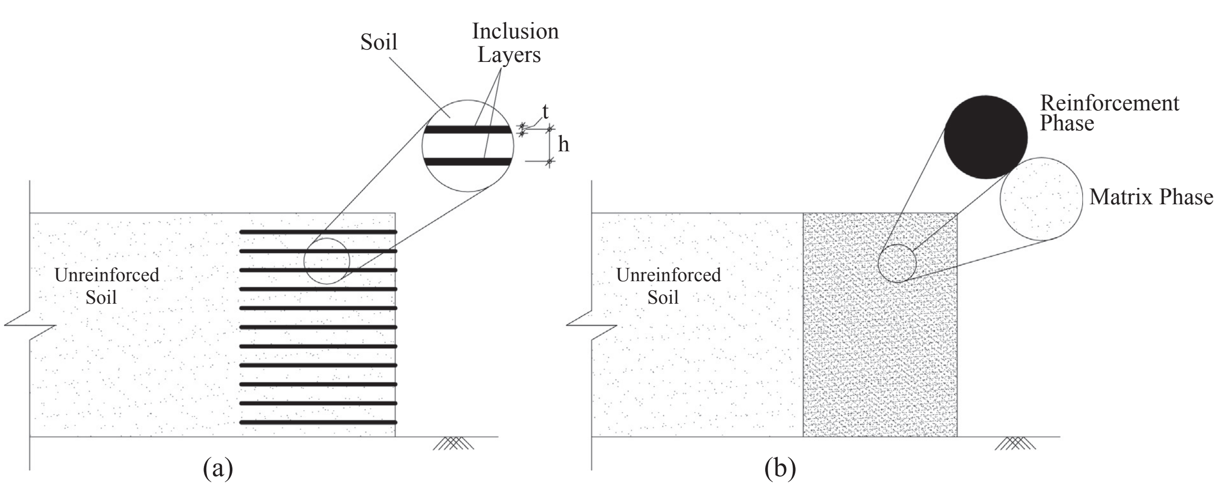

Fig. 1. Schematics of a reinforced soil wall: (a) in discrete form; (b) as a two-phase material.