Numerical Analyses with an Equivalent Continuum Constitutive Model for Reinforced Soils with Angled Bar Components

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Abstract. The discontinuity and hardness variation in the reinforced soil, makes modeling difficult, so use of simple methods that are developed to estimate the heterogeneous field behavior has been found. In this paper, an equivalent continuum constitutive model for three-dimensional analysis reinforced soil in FLAC^{3D}, was developed. The soil characteristics of deformation and strength are considered containing up two sets of reinforcements with arbitrary spatial setting and equivalent stiffness tensor of soil are conducted based on superposition of all components. By new constitutive relationships, anisotropy of reinforced soil can be implemented; however plastic strains can develop in pure soil mass. The model C++ code is written and implemented in FLAC3D and used for modeling of a triaxial compressive test on a soil specimen with one set of reinforcement. The stiffness values calculated by the model are compared with the results from an analytical solution. The results derived are in good agreement with those obtained from analytical method.

Keywords: Reinforced soil · Anisotropy · Equivalent continuum model

1 Introduction

The behavior analysis of reinforced soil directly by means of a classical finite element or finite difference numerical tool, considering to strong heterogeneity, leading almost inevitably to computational difficulties since such reinforced structures have been formed of different elements with different characteristics and behavior. Of course, the small cross-section and very large number of the inclusions (up to several hundreds) that requires a very locally fine meshing, leading to oversized numerical model. Moreover, due to the geometry of the composite reinforced soil, a three-dimensional analysis is needed as well as elastoplastic constitutive models have to be utilized. For all these reasons, the computational cost may eventually be prohibitively large.

In order to overcome such difficulties, the classical homogenization technique appears to be a good way as an alternative approach to direct numerical simulations, since the Non-homogeneous media could be replaced by an equivalent anisotropic

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homogeneous one [1]. Using the advanced techniques of this tool, in finite element (or finite difference) code (performed by Hooper [2]), helps to the problem is simplified and the time of analysis is extremely small [3, 4].

In the present paper, a new extension method of homogenization called the multiphase method (proposed by Sudret and de Buhan [5, 6]) was used and developed for multi unidirectional inclusions. According to this model the reinforced soil is described as the superposition of two mutually interacting continua called phase, which represent the soil and the network of inclusions, respectively. This paper starts from formulation of methods, and then the model is numerically implemented in a specifically three-dimensional version of standard FDM code. The extension model validated by comparison to analytical solutions. The results derived from such a simulation appear to be in good agreement. The aim of the paper is to present and validate a new equivalent medium for reinforced material.

2 Background of Theory and the Model's Implementation

Consider a continuous medium reinforced by a network of uniformly distributed inclusions oriented along arbitrary direction. This composite material model might be viewed as the superposition of two mutually interacting continua, matrix and reinforcement.

As regards the statics of such material, under the action of an external force, the total elastic stress increment tensor $\underline{\underline{\dot{\Sigma}}}$ in the equivalent model is the sum of the elastic stress in each component of the system, i.e. matrix and reinforcement. In a global coordinate system this can be written as follow:

$$\dot{\Sigma}_{ij} = \dot{\sigma}_{ij}^{m} + \dot{\sigma}_{ij}^{r1} + \dot{\sigma}_{ij}^{r2} \tag{1}$$

where $\dot{\sigma}_{ij}^{m}$ is the stress increment in the matrix continua and $\dot{\sigma}_{ij}^{r1}$, $\dot{\sigma}_{ij}^{r2}$. are the stress increment in the reinforcement sets. In local coordinate system, $\bar{\sigma}^{r}$ is not the stress in the reinforcement material. It is a macroscopic stress variable calculated as the axial force F_{inc} developed in the inclusion per unit transverse area of REV (Eq. 2).

$$\bar{\sigma}^{r} = \frac{F_{inc}}{A_{REV}} = \frac{F_{inc}}{s^{2}} \tag{2}$$

which s represents the spacing between two neighboring inclusions. The local coordinate system of bars is oriented such that 3-axis points to inclined direction of inclusion and 1&2-axis is defined perpendicular to bar direction, that together form a right-handed coordinate system. To obtain the total stress (Eq. 1) $\bar{\sigma}^{r}$ must be converted from the local to the global coordinate system, so it is:

$$\sigma_{ij}^{r} = \bar{\sigma}^{r}\left(n_{i}n_{j}\right) \tag{3}$$

In global coordinate system by summing of stiffness matrix of all components, the equivalent elastic matrix of reinforced soil can be determined and implemented.

The user can also determine the number of inclusion sets involved in the analysis that can vary from zero to two sets. An equivalent reinforced soil model with zero inclusion set works as the built-in Elastic model in FLAC3D.

The parameters required for the model are those defining the spatial geometry of the inclusion, i.e. unit vector of inclusions direction and spacing, and the elastic and failure parameters of the soil and inclusions. The bulk and shear moduli of the soil are the only parameters required for elastic analysis.

3 Deformation and Anisotropy Validation

The deformation of a block of soil in a triaxial loading condition is analyzed by two methods: the equivalent soil model implemented in $FLAC^{3D}$ and the analytical method. The model consists of a 1 × 1 × 1 m soil block that contains one set of inclusion in yz-plane at different angles ranging $\beta = 0$ to 90° measured from z-axis. Inclusions are spaced at $S = 0.2$ m. In all models plastic deformations are prevented. Table 1 shows the mechanical properties that are used for these models.

Table 1. Mechanical and strength parameters for triaxial test.

Parameter	Soil	Inclusion
Elastic modulus	1500	150000
Poison's ratio	0.25	—
Cohesion	0	—
Friction angle	25	—
Inclusion area (mm^2)	—	625
Inclusion spacing	—	0.25

Figure 1 shows the variation of the axial stiffness versus inclusion inclination. In comparison with the analytical solution, the equivalent soil model tends to slightly overestimate the deformations for β values in the elementary of the study range. For the assumed mechanical parameters, the difference reaches its maximum of 10% at $\beta = 25°$ (Fig. 2).

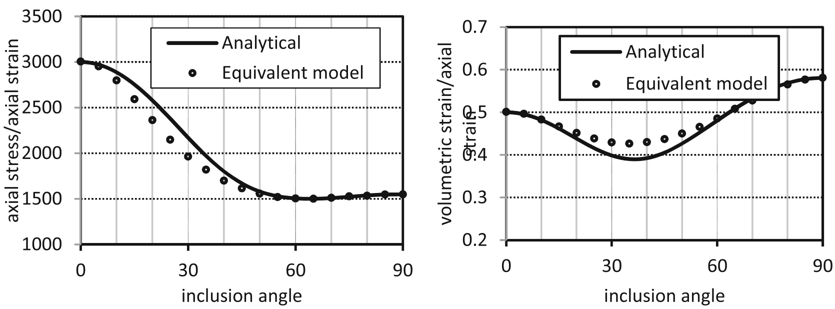

Fig. 1. Axial behavior of reinforced soil in triaxial test

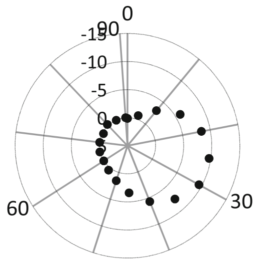

Fig. 2. Difference between calculated axial stress strain ratio by the equivalent model and analytical solution for different inclusion angle

4 Conclusions

A three-dimensional equivalent continuum constitutive model was formulated for reinforced soil masses containing up to two persistent inclusion sets. The model was developed to efficiently handle the deformation anisotropy and stress dependency in reinforced soils. The model was implemented in FLAC3D and the results compared to analytical solutions. The results show that the equivalent soil model provides an efficient tool for deformation analysis of reinforced soil in which the general anisotropy of a soil mass is of importance to the analysis. The analytical method tends to slightly underestimate the axial deformations over the applied range of inclusion angle except for the two cases of $\beta = 0°$ and $\beta = 90°$.

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