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Two-phase model for nonlinear elasto-plastic behavior of reinforced soil structures using Pastor-Zienkiewicz-Chan model for matrix phase

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Abstract

The present study proposes a two-phase model to predict nonlinear elasto-plastic behavior, including deformation patterns and large displacements of geosynthetic-reinforced soil structures under monotonic loading. The two-phase model considers reinforced soil as the superposition of two mutually-interacting continuous phases; the matrix (soil) and the reinforcement (inclusion). The Pastor-Zienkiewicz-Chan model is implemented in a two-phase model as the constitutive law for the matrix phase by which the hardening–softening behavior of the two-phase medium can be considered. The model is applicable for granular soils under drained conditions. Inclusions are treated as linearly-elastic perfectly-plastic material. The perfect bonding hypothesis is assumed between the matrix and reinforcement phases. The approach was validated by comparison of the results with those of plane strain element testing and layered simulation models. Two centrifuge tests on geosynthetic-reinforced soil slopes were then simulated. The settlement, deformation pattern and potential failure surface of the slopes are also investigated. The results indicate satisfactory performance of the model for investigation of the nonlinear behavior of reinforced soil slopes.

Keywords: Two-phase model; Reinforced soil; Nonlinear behavior; Pastor-Zienkiewicz-Chan model; Large displacement; Deformation pattern

International Geotechnical Classification: E01; E13; K14

1. Introduction

Reinforced soil structures are typically composite structures with multi-layered inclusions. The discrete simulation of soil and inclusions is generally used for the behavioral analysis of these structures, especially for displacement analysis under static and dynamic loading; however, analysis of reinforced soil structures using this method is time-consuming. One solution to address this problem is the use of homogenization, which assumes a reinforced soil medium as a homogenous equivalent with anisotropic behavior in macroscopic view (Harrison and Gerrard, 1972; Romstad et al., 1976; de Buhan et al., 1989; Michalowski and Zhao, 1995). de Buhan and Sudret (1999) introduced the two-phase model as an extension of the classic homogenization methods. Their model treats soil mass and inclusion arrays as mutually-interacting, superposed homogeneous continua. The two-phase model is based on the virtual work theorem in continuum mechanics developed by Germain (1986) and Salençon (1996). In this model, inclusions are assumed to be elements showing tensile-compressive behavior. Linearly-elastic perfectly-plastic constitutive laws account for the matrix and reinforcement phases. The perfect bonding hypothesis is

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assumed between the matrix and reinforcements. de Buhan and Sudret (2000) next developed a two-phase model in which the flexural behavior and axial behavior of inclusions are taken into account. They assumed linearly-elastic constitutive law for the matrix and reinforcement phases. Sudret and de Buhan (2001) applied a two-phase approach to simulate rock-bolted tunnels and piled-raft foundations. They used the Mohr-Coulomb yield criterion for a rock-bolted tunnel and Drucker-Prager yield criterion for a piled-raft foundation for the matrix phases. The inclusions were assumed to take only tensile and compressive forces. Hassen and de Buhan (2005, 2006) predicted settlement of a piled-raft foundation subjected to combined vertical and lateral loading. The perfectly-plastic condition was assumed for the matrix and reinforcement phases. They considered the shear, flexural, and axial behavior of the inclusions.

Seyedi-Hosseininia and Farzaneh (2009, 2011) introduced an elasto-plastic bounding surface model with a Mohr-Coulomb yield surface for the matrix phase in a two-phase model to study the nonlinear behavior of a reinforced soil wall under working stress. This model is not suitable for predicting the behavior of reinforced soil structures with large displacements and deformation patterns. The deformation analysis of reinforced soil structures, such as high reinforced soil walls, geosynthetic-reinforced soil (GRS) slopes, and abutments under their own weight and external loads is a challenging topic for researchers. To properly predict the deformation pattern and behavior of such structures under large displacements, appropriate constitutive model have to be applied to the matrix phase.

Several researchers have experimentally and numerically investigated deformation patterns and large displacements of reinforced soil structures. McGown et al. (1978), Tatsuoka and Yamauchi (1986), and Higuchi et al. (1998) carried out plane strain tests on granular samples reinforced using different inclusion materials. Bathurst and Benjamin (1990) constructed and tested a large-scale reinforced soil wall 3 m in height that was step-loaded with a series of surcharge loads up to 80 kPa. The final surcharge increment caused a well-defined failure plane in the reinforced soil mass. Huang et al. (1994) reported failure mechanisms of reinforced sand slopes loaded with a footing. They showed that the bearing capacity of footing could be increased by using stiff reinforcements in the vicinity of active wedge in the corresponding unreinforced slope. They measured load-displacement relations of footing on the reinforced slope. Kodaka et al. (1995) carried out a series of tests on panel-faced reinforced slopes and observed the behavior of the models from initial loading to ultimate failure. They applied a linearly-elastic finite element method and rigid-plastic finite element method to simulate the panel-faced reinforced slopes from the beginning of loading to ultimate failure. Abu-Farsakh et al. (2013) experimentally investigated the behavior of geosynthetic-reinforced sand under the footing loading. They reported pressure-settlement curves for model footing tests in different conditions.

The present work developed a two-phase model to predict the nonlinear behavior of reinforced soil structures under strong loading and the conditions for large displacements based on infinitesimal deformation theory. The Pastor-Zienkiewicz-Chan (PZC) (Pastor et al., 1990) model was used for the behavior of soil (matrix). This model enables the two-phase model to simulate hardening-softening behavior of the reinforced soil and therefore to predict large displacements. The most important improvement of the current research in comparison with the authors' previous works is implementing the PZC model for the matrix phase in the two-phase model. The PZC model gives the two-phase model the capability to simulate strain softening of the reinforced soil mass. The previous works could simulate the behavior up to the peak strength of the reinforced soil. The main advantage of the PZC model is its incremental nonlinear stress-strain format that simply captures the stress-strain behavior of a material. It can also simulate a strain-stress response for different initial conditions under monotonic and cyclic loading without an explicit definition of yield or the plastic potential surface (Ling and Liu, 2003). The used PZC model is for granular soil.

The reinforcement phase was assumed to be a linearly-elastic perfectly-plastic material with a Tresca yield criterion. The time-dependent properties of the materials and, consequently, the loading rate effect were not been considered in the present analysis. Furthermore, the two-phase model was validated using the centrifuge test, which is a very fast experiment compared to the process of construction. Therefore, the predicted displacements in the two-phase model may be lower than the results at the end of construction; the difference between them mainly depends on the viscosity coefficient of the used geosynthetics.

Several researchers have investigated the effect of creep on the behavior of GRS walls. Sawicki (1999) presented experimentally the effect of creep on lateral displacements of a reduced scale GRS wall. He reported that the maximum lateral displacement under surcharge loading was increased 36% after 552 h. Onodera et al. (2004) presented the long-term behavior of three large scale GRS walls under surcharge load. The increase in the maximum lateral displacement for type 1 was 51% after 4570 days, for type 2 it was 21% after 4570 days, and for type 3 it was 34% after 2768 days. The perfect bonding hypothesis was assumed between the matrix and reinforcement phases.

The proposed two-phase model was implemented in Flac 2D, a well-known finite difference code. All simulations are in the drained condition.

2. Proposed two-phase model

This section summarizes the two-phase formulation for a 2D reinforced soil system. A detailed description of the