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学位論文の要旨（論文の内容の要旨）
Summary of the Dissertation (Summary of Dissertation Contents)

論　文　題　目
Dissertation title

Multiscale Characterization of Geotextile-Reinforced Granular Soil

広島大学大学院国際協力研究科
Graduate School for International Development and Cooperation, Hiroshima University
博士課程後期　開発科学　専攻
Doctoral Program　Division of Development Science
学生番号　D132535
Student ID No.
氏　名　CHENG HONGYANG　㊞
Name　Seal

Geosynthetic-reinforced soils are heterogeneous and discontinuous geomaterials that can be designed with great flexibility. For environmental and economical reasons, the application of geosynthetic reinforcements in the construction of infrastructures is becoming prevalent, along with the increase of the diversity in reinforcement forms, e.g. discrete fiber, planar layer, cellular encasement, to name a few. Despite high improvement on the stiffness and strength, the interactions between granular particles and geosynthetic inclusions complicate the stress history, deformation pattern and fabric characteristics in the reinforced soils, posing formidable challenges to the predictive models of geosynthetic-reinforced soils. Considering the `discrete' nature of granular soils, this thesis aims to obtain a better understanding of the behavior of geosynthetic-reinforced granular soil via multiscale characterization and modeling of soil--geosynthetic interactions, and thence develop analytical solutions for this complex geomaterial for practical usage.

The Discrete Element Method (DEM) is utilized to provide a cross-scale interpretation of the micromechanics in the granular soil with different forms of geosynthetic reinforcement. The sequential data assimilation based on recursive Bayesian estimation is employed to calibrate the mesoscale response of the DEM models of Toyoura sand. With the assumptions derived from the newly obtained understanding, a close-form elastoplastic solution is proposed for geotextile-wrapped soil under compression. In order to solve general soil--geosynthetic interaction problems, the concurrent multiscale modeling strategy is incorporated into the hierarchical multiscale framework based on a coupled finite element method (FEM)/DEM approach, avoiding both the scale limitation of DEM models and the continuum-based constitutive models of a great complexity for geosynthetic-reinforced soils.

The sequential data assimilation technique, i.e. the particle filter, identifies the true values for the micro parameters with high accuracy in reproducing the experimental measurement. Instead of a single set of parameters, the identification comes in the form of probability density functions, which is deemed more objective than most optimization methods.

The DEM model of geotextile-wrapped soil is fabricated in a assembling--filtering--expanding packing generation process, using the calibrated mesoscale DEM model as the representative volume. The woven geotextile fabrics are discretized as an assembly of particles linked with stretching springs. Linear local and global stress paths are observed with the same slope until the rupture of the geotextile. Under simple shear, the global stress path approaches the critical state line first and then turns to the compression line of the wrapped soil. The representative volumes in the middle undergo some local loading--unloading stress paths, which may account for the high damping of sand-filled geotextile containers during cyclic shear. The reduced fabric anisotropies of the normal and tangential force chains suggest greater confinement from the lateral sides of the geosynthetic container in either loading course.

Having validated the DEM model of geotextile-wrapped granular soil, a comparative study is carried out to examine the influence of reinforcement form and geotextile stiffness on both the macroscale response and the microscale characteristics of the reinforced soil. The simulations show that the stiffness and strength of the wrapped soil are greater than those of the layered soil, and the amount of dilation within the reinforced zone is significantly larger in the latter than in the former. Consistent local and global stress paths are observed, suggesting analogous confinement mechanism in both reinforced soils. Shear deformation is relatively severe in the layered soil with notable localization near the edges, showcasing the ability of the wrapped soil to sustain shearing.

To lay a foundation for the analytical solution for geotextile-wrapped soil, the soil-geotextile interface behavior, principal stress distribution, and stress-strain behaviors of the constituent soil and geotextile are analyzed, considering a wide range of geotextile tensile stiffness in the DEM simulations of uniaxial compression tests on geotextile-wrapped soil. From the DEM analysis, a unique near-failure state line, which predicts the difference between q/p and q_f/p at failure state, is identified for geotextile-wrapped soil under uniaxial compression. Dilation rates are related with stress ratios via a unique linear correlation regardless of geotextile tensile stiffness. The analytical model is validated by comparing the close-form solutions with the macroscopic responses of the DEM model under uniaxial compression. Though originally developed from uniaxial compression simulation results, the analytical solutions are in good agreement with the DEM solutions in triaxial loading conditions.

The scale of the above mentioned DEM models is largely restricted by the high computational cost. To circumvent this restriction, a multiscale model based on a coupled FEM/DEM approach is employed for general soil--geosynthetic interaction problems. The displacement in the granular soil is solved in the hierarchical multiscale framework, while the geosynthetic inclusion that prescribes the boundary conditions are modeled concurrently by discrete bar elements. The responses of both multiscale domains are communicated and updated in an explicit time integration scheme. The predicative capacity of this model is examined in two numerical examples, i.e., shape-forming and pull-out tests. The multiscale approach is proved to a versatile tool for handling a variety of the soil--geosynthetic interaction problems. The shape-forming multiscale simulation reveals increasing stress level and decreasing anisotropy at the local point near the top boundary where shear strain is larger than the rest of the soil domain. In the pull-out simulation, vortex-like displacement field is observed with the origin close to the left end of the geosynthetic inclusion. Such pattern is further confirmed by the dilative volumetric response at the local Gauss point above the geosynthetic inclusion.