DEVELOPMENT AND APPLICATION OF NUMERICAL METHODS FOR UNSATURATED SOIL MECHANICAL ANALYSIS AND RAINFALL-INDUCED LANDSLIDE SIMULATION FOCUSING ON MATRIC SUCTION

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出版情報：Kyushu University, 2021, 博士（工学）, 課程博士
バージョン：
権利関係：

（様式２）

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論 文 名：DEVELOPMENT AND APPLICATION OF NUMERICAL METHODS FOR UNSATURATED SOIL MECHANICAL ANALYSIS AND RAINFALL-INDUCED LANDSLIDE SIMULATION FOCUSING ON MATRIC SUCTION
(サクションに着目した不飽和土力学挙動の解析および降雨による斜面崩壊シミュレーション手法の開発と応用)

区　　分：甲

論 文 内 容 の 要 旨

Geotechnical problems such as slope stability and post-failure movement are closely related to mechanical behaviors of unsaturated soil. Besides cohesion and friction, matric suction is one of the major factors controlling the mechanical behaviors of unsaturated soil. For example, rainfall-induced slope failure, which is one of the widespread natural hazards in the unsaturated zone, is basically caused by dissipating matric suction in the topsoil. Therefore, it is important and necessary to clarify the mechanical behaviors of unsaturated soil and to develop a novel method for slope stability and post-failure movement analysis by considering matric suction properly.

Matric suction is directly related to the water content of unsaturated soil, and it can be represented by the so-called soil-water characteristic curve (SWCC). It has been found that SWCC is different from soil to soil from laboratory experiments. However, it has not been fully clear why SWCC is so different and what are the major influence factors up to now because the origin of matric suction is complex; it is also not entirely clarified how matric suction contributes to shear strength. Furthermore, matric suction is simply taken as an apparent cohesion to reinforce shear strength in the existing slope stability analysis. Besides it is difficult to determine the proper apparent cohesion from matric suction, matric suction would not affect post-failure movement in the existing analysis method. Therefore, in order to clarify the mechanical behaviors of unsaturated soil and to develop a novel method for slope stability and post-failure movement analysis, the following issues should be solved: (1) how to simulate matric suction numerically from both capillary suction and adsorption suction; (2) how to clarify the influence factors of SWCC from different soils; (3) how to clarify contributions of matric suction to shear strength; (4) how to develop a method for slope stability and post-failure movement analysis based on matric suction in rainfall-induced landslide study.

This study aims at solving the above issues by developing numerical methods for microscopically simulating the mechanical behaviors of unsaturated soil and for macroscopically analyzing the effect of matric suction on rainfall-induced landslides based on Discontinuous Deformation Analysis (DDA). At first, a capillary suction model and an adsorption suction model are proposed based on capillary theory and double-layer theory for calculating matric suction, and a microscopic DDA simulation method (called micro_DDA) is developed by adding suction forces separately on adjoining DDA blocks. Then, the major influence factors of SWCC are analyzed and clarified with a series of DDA models from various soils and saturations. In addition, how matric suction reinforces the shear strength of soil is investigated and the contributions of matric suction to shear strength is clarified. Finally, a novel method (called macro_DDA) is developed by adding the equivalent suction force on DDA blocks directly so that geoengineering problems related to matric suction can be easily simulated. And the slope stability and post-failure movement of a real rainfall-induced landslide in the North Kyushu area are analyzed to show the usefulness of macro_DDA.

This thesis comprises the following chapters:

Chapter 1 introduces the background, the scope and the objectives of this study, and the organization of the thesis. The studies on landslides and mechanical behaviors of unsaturated soil are also introduced.

Chapter 2 reviews several research topics on unsaturated soils. At first, the concepts of effective stress, matric suction, SWCC, shear strength, microstructure are introduced. Then, the slope stability analysis by taking matric suction as an apparent cohesion to reinforce shear strength is reviewed in detail. Finally, the fundamental theory and the contact mechanism of DDA are introduced. The key issues to be solved are clarified.

Chapter 3 develops micro_DDA for microscopically simulating matric suction of unsaturated soils by incorporating a capillary suction model and an adsorption suction model into the original DDA. The matric suction calculated based on capillary theory and double-layer theory is acting as the suction force exerted to the surface of adjoining DDA blocks which represent soil particles. The capillary suction is modeled by the following three steps: (1) potential capillary bridges are searched and determined among soil particles under a designated capillary radius; (2) capillary water distribution is determined to meet the water content in the multi-particle system; (3) surface tension and matric suction are added to soil particles based on Young-Laplace equation. In adsorption suction model, bound water and clay minerals are assumed as "clay layer" and evenly covered around DDA particles, and the suction force is calculated based on double-layer theory by the same three steps as for capillary suction model. In order to validate micro_DDA, the SWCCs of pure Toyoura sand and sand-clay mixture as two cases are simulated, and the obtained results are in good agreement with the experimental results.

Chapter 4 analyzes some influential factors of SWCC and shear characteristics of unsaturated soil based on the developed micro_DDA. At first, the influential factors such as particle size, specific surface area (for cohesive soil), and contact angle are investigated. It is found that (1) the particle size has less influence on SWCC for cohesionless soil than cohesive soil; (2) specific surface area can influence SWCC significantly; (3) contact angle influences hydraulic hysteresis of SWCC distinctly when it is over 20°. It is also shown that micro_DDA has advantages comparing with experimental analysis because it can easily and quickly assess the influence of the different specific surface area and contact angles on SWCC, which is difficult and time-consuming for experimental methods. And then, the direct shearing test of Toyoura sand is simulated, and the "peak effect" of the shear strength with respect to matric suction is reproduced and investigated. The "peak effect" of sand can be explained by the proposed micro parameter *CSN* (so-called number of the capillary bridge), which is quantitatively in accordance with the peak shear strength. Since adsorption suction is an indispensable factor for cohesive soil, when the contact area of the clay soil decreases slightly, the adsorption suction becomes the dominant factor for apparent cohesion, which well explains why there is hardly a "peak effect" phenomenon for cohesive soil.

Chapter 5 develops macro_DDA for analysis of macro geoengineering problems considering matric suction in DDA. In the existing slope stability analysis method, matric suction is taken as apparent cohesion to reinforce shear strength. However, matric suction reinforces both shear strength and tensile strength by increasing normal stress, also, matric suction still affects post-failure movement. For this reason, macro_DDA is developed by considering the mechanical behavior of matric suction as an equivalent suction force added among DDA blocks. The equivalent suction force is a function of saturation and can be estimated from SWCC. Macro_DDA is validated by using a single block sliding model and a multi-blocks sliding model. The evaluated safety factor is in good agreement with the theoretical solution. It is also found that the runout distance is related to the degree of saturation which shows good agreement with the experimental results. Finally, a practical rainfall-induced landslide is simulated and discussed. The simulation results show that the dissipation of matric suction in the topsoil is a determining factor for this slope failure, and matric suction still affects the run-out distance after slope failure.

Chapter 6 concludes the results and achievements of the study as well as states the relevant issues that need to be solved in future studies.