学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　博士（工学）　氏名　羅 斌

学 位 論 文 題 名

Proposal of a constitutive model for the behavior of unsaturated soils subjected to freeze-thaw action
(凍結融解作用を受ける不飽和土の挙動解析に対する構成モデルの提案)

The failure of earth structures subjected to freeze-thaw frequently occurs in seasonal cold regions like Hokkaido, Japan. Frost heave and thaw settlement are deemed as two main factors affecting the performance and safety of infrastructures like road, railway, pipeline and soil slope. Subsurface soils are unsaturated in most cases, however, the estimation method on frost heave and thaw settlement of unsaturated soil are not well established. This study focuses on numerical modeling of freeze-thaw behavior of unsaturated soil, especially on freeze-thaw deformation.

A coupled thermo-hydro-mechanical (THM) model is presented in detail first, which captures the main behaviors of soil subjected to freeze-thaw. For instance, the phase change of water-ice, the reduction of permeability induced by freezing, together with the stiffing of frozen soil are all modeled. More specially, practical experimental equations are applied to model frost heave and thaw settlement. On purpose of validating model, frost heave test was simulated. The model can simulate the correlation between frost heave and water absorption under saturated condition. The influence of overburden pressure on freeze-thaw deformation is also reproduced, however, the model fails to estimate the cooling rate effect. Then, a pavement structure located above a box culvert was simulated to investigate uneven upheave of pavement. After that, stress change in pavement induced by freeze-thaw was studied.

Further development was conducted to overcome the limitations of the above-mentioned model. Recent achievements and progress in unsaturated soil and frozen soil are integrated into the model. Modified governing equations are presented, together with better consideration on nonlinear soil properties. More specifically, attention is paid to the analogy between soil water characteristic curve (SWCC) and soil freezing characteristic curve (SFCC), along with suction induced freezing point depression. Furthermore, ice segregation criteria, frost heave, and direction of thaw settlement are modeled in a more rational way. The validity of the newly proposed model was examined by simulating frost heave test under saturated and unsaturated conditions. Finally, freeze-thaw behavior of an unsaturated soil slope in the seasonal cold region was simulated to verify the applicability of the proposed model for a field-scale problem. The thermal pattern of soil slope is reproduced in which frost penetration at slope top is deeper than that at slope toe and isothermal is not parallel to slope surface. Water redistribution induced by freezing is reproduced together with water-ice phase change and ice accumulation. Mechanism of unique freeze-thaw deformation pattern is revealed. Frost heave generates in heat flow and/or thermal gradient direction, not necessary to be perpendicular to slope surface, while thaw settlement mainly develops along gravity direction.

In conclusion, a numerical model is proposed for freeze-thaw behavior of unsaturated soil. It is found that the numerical model proposed in this study performs well for estimation on frost have and thaw

settlement. The model is ready for field-scale applications to serve design, construction, and maintenance of earth structure in cold regions, although some limitations exist, and further verifications are recommended.