論 文 の 内 容 の 要 旨

論文題目　CONSTITUTIVE MODELLING AND FINITE ELEMENT ANALYSIS OF REINFORCED SOILS
(砂の弾塑性構成モデル化及び補強土の変形・破壊数値解析)

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In the elasto-plastic models for soils, the hardening function controls the development of yield locus as the soil yields. The hardening parameter involved in the hardening function is usually a state parameter, which is independent of previous stress history and current stress path direction. For soils, certain type of plastic strain component, or plastic strain energy, has been usually employed as the hardening parameter.

The results from previous FEM analyses using a plastic strain-hardening constitutive model showed that the FEM simulation exhibited larger pre-peak stiffness and smaller pre-peak strains and deformation in the stress-strain relationships in plane strain compression tests and the load-settlement relationships in bearing capacity model tests. The results from recent plane strain compression tests employing loading tests along a wide variety of stress paths suggested that this discrepancy is mainly due to the effects of intermediate local stress paths on the strains of soil, which were not taken into account in the previous FEM analysis. The FEM analysis also showed that the local stress paths in the failing zones in reinforced soils in plane strain compression tests and in the boundary value loading tests, such as bearing capacity tests are similar to those of anisotropic compression at stress ratios close to that at failure. The previous constitutive modelling of the stress-strain behaviour of soils are usually based on the results from isotropic compression tests and loading tests at a constant confining pressure.

The objectives of the present research are therefore;

1) to develop a new class of rigorous elasto-plastic model for geomaterials, based on the results from the recent plane strain compression tests;
2) to incorporate the model in the FEM code; and
3) to apply this model to several boundary value problems. The problems analyzed in the present study include the plane strain compression tests and the bearing capacity model tests on sand

without or with reinforcement.

To validate the basic capability of the FE method used, results from a series of plane strain compression behavior on the unreinforced sand specimen as well as on reinforced sand specimens with geogrid reinforcement were first simulated by a FEM analysis incorporating the strain-hardening model for sand. Not only the pre-peak stress-strain behavior of the unreinforced and reinforced specimens, but also the peak strength, the post-peak behavior and dilatancy characteristics, from the FEM analysis are well comparable with those from the physical tests. The effects of reinforcement rigidity and covering ratio are also well simulated. The analysis showed that the effects of covering ratio for each grid layer could be much more important than the total tensile stiffness of reinforcement like as geogrid in the present study. The relationship between the reinforcement covering ratio in the physical tests and the equivalent interface friction angle for the FEM analysis that provides the same reinforcing effect has been presented. By using this relationship, it becomes possible to analyse the soil reinforced with reinforcement having a three-dimensional (3D) structure in the scale of soil particle size, such as geogrid, by using a respective appropriate equivalent interface angle between the reinforced and soil. The mechanism of tensile-reinforcing has been analysed based on local stress paths within the reinforced sand obtained from the FEM analysis. It is shown that the failure of reinforced sand specimen in plane strain compression is considerably progressive, in particular, the global peak state is attained when the local axial stress is either decreasing or increasing after the respective maximum local principal stress ratio has been attained.

A new elasto-plastic constitutive model was developed based on one unique stress history-independent work hardening parameter. The basis of the proposed model is a unique relationship between the modified strain energy quantity and the instantaneous stress state, which is dependent of stress history and stress path. The model was developed based on the results from a series of recent drained plane strain tests on saturated dense Toyoura sand with precise stress and strain measurements, performed along many stress paths. The proposed model is capable of simulating the effects on the deformation characteristics of stress history, stress path, pressure level, void ratio and inherent anisotropy. The work softening associated with strain localization into a shear band is also taken into account. The new constitutive model is validated by a direct comparison between the numerical and experimental stress-strain behaviour.

A FEM simulation of plane strain compression tests on unreinforced dense Toyoura sand and the one reinforced with planar reinforcement having a wide range of stiffness is presented. The FEM analysis, incorporating the proposed constitutive model, is validated by a direct comparison between the numerical and experimental results. Both global and local stress-strain behaviors observed in the physical PSC tests on both unreinforced and reinforced sand specimens have been successfully simulated by the newly improved FEM code. A better insight into the internal mechanism of reinforced could has been obtained from the FEM analyses. The new FEM code, incorporating with the proposed work hardening model, have much better simulated the results from the physical PSC tests than the one with the previous strain hardening model. In particular, the problems with the previous FEM analysis, the over-estimation of pre-peak stiffness and under-estimation of the strain and deformation at the failure state, have been solved. This is because the proposed newly proposed constitutive model is capable of properly simulating the stress-strain behaviour of sand for loading along a wide variety of stress paths.

A FEM analysis, incorporating the proposed constitutive, has also been conducted to simulate results from a series of plane strain bearing capacity laboratory tests performed on the unreinforced sand model ground as well as the one that is reinforced with linear, tensile reinforcing members placed horizontally beneath a strip footing. Global load-settlement behaviour, local strain fields in the sand, including shear banding patterns, and strains in the tensile reinforcement observed in the physical plane strain bearing capacity tests have been successfully simulated by the proposed FEM analysis method. The new FEM code, incorporating the proposed work hardening model, have much better simulated the results from the physical PSC tests than the one with the previous strain hardening model. The problem with the previous FEM analysis, underestimating of pre-peak footing settlement, has been improved in the present analysis, validating the newly proposed constitutive model.

In conclusion, a newly elasto-plastic constitutive model with a non-associated flow rule and isotropic work-hardening-softening properties with a unique stress history-independent hardening rule for granular geomaterial, has been proposed. The proposed model is capable of successfully simulating the strength and deformation characteristics for a wide variety of stress histories and stress paths, taking into account elastic cross-anisotropy, pressure level, anisotropy, density and the strain localization into shear band. The FEM analysis incorporating the above-proposed work hardening constitutive model can simulate the behaviour of sand in several boundary value problems in the geotechnical engineering better than the previous one, incorporating a strain-hardening model.