主　論　文　の　要　約

論文題目　**Development of *u*–*w*–*p* Formulation-Based Soil-Water Coupled Finite Deformation Analysis and Elucidation of Inertia Force-Induced Phenomena**
(*u*–*w*–*p* formulation に基づく水～土骨格連成有限変形解析手法の開発と慣性力由来の諸現象の解明)

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論　文　内　容　の　要　約

The soil mechanics research group at Nagoya University has developed the dynamic/static soil-water coupled finite deformation analysis code ***GEOASIA***, whose applicable range has been extended for developing the all-round geo-analysis without distinction of the types and states of soils.

While the incorporation of the SYS Cam-clay model describing the soil skeleton structure contributed to the seamless description of sandy – clayey soils, the rate-type deformation analysis based on the updated Lagrangian method achieved the consistent framework for solving from the deformation problem to the failure problem. The time-integration of the equation of motion also enabled the coherent application of the analysis to the dynamic/static problems.

However, there still exists a limitation in ***GEOASIA*** in terms of the applicability to the highly-permeable soils due to the utilization of the ***u***–*p* formulation. The ***u***–*p* formulation assumes the static pore water permeation, i.e., sufficiently small relative acceleration of the fluid phase viewed from the solid phase against that of the solid phase. Although the utilization of the ***u***–*p* formulation dramatically reduced the calculation cost against the original formulation, the negligence of the fluid relative inertia caused difficulties for conducting the soil-water coupling analysis for the highly-permeable soils which accompany the dynamic relative motion of the fluid phase. Therefore, to overcome the limitation of the $\boldsymbol{u}$–p formulation, the original governing equation should be solved for extending the applicability of ***GEOASIA*** to the highly-permeable range. The scheme of the direct calculation of the original governing equation of soil-water coupling analysis is called as full formulation (especially termed the $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation when discretizing the fluid motion by the relative averaged flow rate $\boldsymbol{w}$).

The present research aims to construct the $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation-based soil-water coupled finite deformation analysis without the assumption of $\boldsymbol{u}$–p formulation. Needless to say, the $\boldsymbol{u}$–$\boldsymbol{w}$–p analysis is expected not only to be a tool for analyzing highly permeable soils but also to be utilized as a comprehensive method for solving soil-water coupling problem without the distinction of low and highly-permeable materials regardless of the setting of Δt whose smaller value is usually required in the failure/large deformation problems.

The benefit of overcoming the $\boldsymbol{u}$–p limitation based on $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation is not limited to the wide range of applicability for highly-permeable soil. The characteristic phenomenon caused by the inertial flow of pore water can be observed at the inapplicable range of the $\boldsymbol{u}$–p formulation. Even the solutions of the typical problems of soil mechanics (i.e. seepage, deformation of specimen, consolidation, and wave propagation) exhibited the specific features of their solutions due to the consideration of the fluid inertia. The specific phenomena were introduced and the comprehension was acquired through the discussion.

The following is the outline of the dissertation:

In Chapter 2, the governing equations and their spatiotemporal discretizations of the $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation-based soil-water coupled finite deformation analysis were introduced. The equation of motion of the fluid phase was counted as a governing equation for obtaining the averaged flow rate of pore water $\boldsymbol{w}$ simultaneously. Conforming to the original scheme of $\boldsymbol{u}$–p formulation in ***GEOASIA***, the rate-type equation of motion including the jerk terms was solved for employing the rate-type elasto-plastic constitutive model (SYS Cam-clay model). Moreover, to utilize the updated Lagrangian method to the $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation, the relative reference of the motion of fluid phase against the solid phase (i.e. the Eulerian observation of the fluid phase against the Lagrangely observed solid phase) was proposed. By defining the flow rate $\boldsymbol{w}$ on the Lagrangian frame of the solid phase, the preparation of independent grids of the solid phase and the fluid phase (cf. material point method) was no longer necessary. Furthermore, the installation of $\boldsymbol{w}$ as an unknown variable made the soil-water coupling equation simple, which strictly ensured the mass conservation law.

In Chapter 3, the static/dynamic seepage analysis was conducted based on $\boldsymbol{u}$–p/$\boldsymbol{u}$–$\boldsymbol{w}$–p formulation by fixing the motion of the solid phase as the verification of the analysis code. As the result of $\boldsymbol{u}$–$\boldsymbol{w}$–p calculation, the accelerating flow of pore water that finally achieved the steady flow at the equilibrium of the head gradient and the Darcy's resistance was solved. Furthermore, two-dimensional analysis of expanding flow was also conducted for verifying the convective terms and undrained linear constraint condition.

In Chapter 4, the immediate settlement problem of saturated soil was solved by the $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation considering the wide applicable range for the highly permeable soil and the small time increment Δt. The $\boldsymbol{u}$–$\boldsymbol{w}$–p calculation heuristically discovered the inertia-induced phenomena occurred in the out range of $\boldsymbol{u}$–p formulation, i.e., S-shaped/non-harmonic oscillation in the settlement--time curve and inconsistent immediate pressure at the beginning of the calculation. Through the comparison of the $\boldsymbol{u}$–$\boldsymbol{w}$–p analysis result with a theoretical solution of the damped wave equation, these characteristic features of the $\boldsymbol{u}$–$\boldsymbol{w}$–p solution has been comprehended as the inertia-induced phenomena emerged under the instantaneous load application and the pore water incompressibility.

In Chapter 5, the efficacy of $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation was confirmed through the deformation analysis of an undrained plane-strain specimen. As a $\boldsymbol{u}$–$\boldsymbol{w}$–p solution to the rapid loading on the highly-permeable specimen, the dynamic pore water migration exhibiting propagation/rotation flow inside the specimen was obtained. The vortex that could not be produced from the static Darcy’s law was solved due to the consideration of the fluid inertia. It was also revealed that the fluid inertia in pushing/pulling direction toward the pedestal increased/decreased the reaction force that fluctuates the apparent behavior of the specimen. The proper work of the undrained constraint condition imposed on the moving boundary was confirmed.

In Chapter 6, the oscillation problems with the applications of harmonic load excitation and harmonic ground motion were solved based on $\boldsymbol{u}$–p and $\boldsymbol{u}$–$\boldsymbol{w}$–p formulations. The applicable range of the $\boldsymbol{u}$–p calculation was inspected (which almost conforms to the $\gamma_{\theta 1}$ criterion except the applicable cases even exceeding the criterion with sufficiently static case) and the versatile applicability of the $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation outside of the $\boldsymbol{u}$–p limitation was confirmed. The solution of $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation performed the inertia-induced phenomena (i.e. the transition/resonance response for highly-permeable soil and the inconsistent amplitude of the pore water pressure) at the outside of the applicable range of $\boldsymbol{u}$–p formulation. It was also confirmed that the satisfaction of the $\gamma_{\theta 1}$ criterion derived from the physical meaning of the soil-water coupling equation does not ensure the satisfaction of the $\boldsymbol{u}$–p assumption. The relative convection was also indispensably occurred even in the cases satisfying $\gamma_{\theta 1}$ criterion. Furthermore, the applicability of the $\boldsymbol{u}$–p formulation was systematically marshaled with indicators calculated by $\boldsymbol{u}$–$\boldsymbol{w}$–p formulation. It was confirmed that $\boldsymbol{u}$–p calculations tended to fail when the corresponding $\boldsymbol{u}$–$\boldsymbol{w}$–p calculation exhibited significant magnitude of relative acceleration, crucial infringement of the $\boldsymbol{u}$–p assumption, and indispensable emergence of relative convective term.