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論文内容の要旨

Liquefaction is one of the major threats to structures constructed on a sandy ground. Making clear the mechanism of liquefaction is one of the main objectives of geotechanical researchers and engineers. In many cases, we have to deal with sand under repeated liquefaction and consolidation condition. For instance, during an earthquake, the main-shock may come followed by many after-shocks. A sandy ground maybe firstly liquefy in the main-shock, and then liquefy again in the aftershocks. So, predicting the behaviors of soil under repeated liquefaction and consolidation seems important because the following liquefactions may cause further damage to structures. However, few studies have been done in this field. The main objective of this research is to investigate the mechanical behavior of sand under repeated liquefaction and consolidation, including experimental study and numerical simulation.

In experimental study, a medium-sized shaking table apparatus was utilized to investigate the repeated liquefaction and consolidation behaviors of a sandy ground. For an initially made saturated loose sandy ground, we firstly applied a shaking motion to let the ground liquefied. After the motion stopped, the ground consolidated and excess pore water pressure (EPWP) dissipated. After EPWP had completely dissipated, we applied the same input motion once more to let the ground liquefy again, and then consolidate again. By this way, the ground was shaken three times in succession and become denser and denser for the reason that pore water flowed out from ground. In the whole process of repeated liquefaction and consolidation, the responses of the ground, including acceleration and EPWP, were measured in detail. Another objective of this experiment is to investigate the stiffness recovery process of ground during consolidation process. Because stiffness of ground cannot be measured

directly, we calculated ground stiffness from shear velocity with the use of hammering method.

Following experimental study, a new elasto-plastic constitutive model that can describe liquefaction behaviors of sands with different densities was proposed. The model was based on the concept of SYS Cam-clay model, which was proposed by Asaoka et al (2002). It inherits the advantage of SYS Cam-clay model that it can describe the liquefaction behaviors of sands with different densities using unique values of material parameters, which do not depend on density, but just depend on what material the sand is. The model provides an approach for describing the stress-induced anisotropy together with a new evolution rule for changes in overconsolidation, by which the mechanical behavior of soils subjected to cyclic loading under undrained conditions, including the cyclic mobility of medium dense sand, can be uniquely described. Meanwhile, the physical meaning of these types of behavior for different soils can be explained efficiently with the concepts of overconsolidation, structure, and stress-induced anisotropy.

In liquefaction analysis of a boundary value problem (BVP), a two-phase field theory that can properly take into account the interaction between solid and fluid is very important. In this thesis, the two-phase field theory, which was originally proposed by Oka et al (1991, 1994), was extended using the finite deformation algorithm. In this two-phase filed theory, the displacement of solid, u, and the pore water pressure of fluid, p, are taken as the basic variables in the governing equations. Both FEM (Finite Element Method) and FDM (Finite Difference Method) are used to discretize the field equations in space. FEM is used for the discretization of the equation of motion for the mixture, and FDM is used for the discretization of the continuity equation for the pore fluid. Newmark-β method is employed to discretize the field equations in time.

At last, combining the proposed model and the two-phase field theory, a numerical analysis was conducted using a FEM program DBLIVE to simulate the process of repeated liquefaction and consolidation. The numerical simulation aims to reproduce the three cases of shaking-table tests, in which the model ground was shaken three times in succession and became denser and denser after each shaking. In the numerical calculation, the process during shaking was simulated by a dynamic soil-water coupled analysis, while the process of dissipation of EPWP was simulated by a static consolidation analysis. The values of material parameters were the same in all stages. The state of soil elements valuated by five state parameters was only prescribed at the very beginning and the values of these parameters was delivered automatically to the next stage of the analysis in the whole process, which was totally the same as what has been done in the model test. Comparisons between the experiment and the numerical simulation show that the numerical simulation is

capable of reproducing almost all main characteristics of the repeated liquefaction-consolidation of sandy grounds with different densities, such as the mechanical behavior pre- and during liquefaction, the settlement in post-liquefaction consolidation and the influence of density on the accumulation of excessive pore water pressure (EPWP) in repeated strong motions.

論文審査結果の要旨

本論文では、地震時における砂地盤の液状化現象について、液状化と圧密を繰り返す過程を精度良く予測するための解析技術の開発を目指した。

まず、砂地盤の液状化とそれに引き続く圧密現象、さらには再液状化過程を理解するために、大型振動台試験装置を用いた模型実験を実施している。用いた大型振動台試験は空圧制御型の新しいタイプのもので、その制御および実験準備についても、マニュアル作成などの地道な作業を継続し、今後の実験的研究の基盤整備を完了した。初期地盤に、繰り返し振動を付加することにより、初期においてゆる詰めの地盤が、液状化後の再圧密過程において地盤が高密度化し、液状化しにくくなる特性を見いだしている。また、液状化直後の地盤の剛性回復を求めるために、新たにハンマリング法を提案し、発生した過剰間隙水圧の消散過程と剛性回復過程の関係を丁寧に求めている。

これらの現象を精度良く解析するために、1)液状化－圧密繰返し過程を統一的に表現できる構成式を新たに提案した。提案した構成式は、砂地盤のみならず粘土地盤についても適用できるもので、過圧密、構造、異方性といった地盤材料特有の性質を統一的に説明できることを証明した。2)提案した構成式を有限変形土～水連成ＦＥＭに導入した。提案したＦＥＭ手法を用いてモデル実験を解析した結果、提案する解析手法は液状化－圧密繰返し過程を精度良く再現した。この成果は、今後の土木構造物の耐震設計を考えるにあたり、非常に重要である。

最終試験結果の要旨

八嶋　厚、杉戸真太、能島暢呂、張　鋒および沢田和秀で構成する審査委員会は、本論文および別刷りなどを慎重に検討した。本論文は学位論文として十分完成された内容を有していること、提出された学位論文および発表論文は、申請者により書かれていることを確認した。また最終試験（公聴会）を平成19年1月25日に開催し、審査委員会での審査の結果、合格と判定した。