Development of Hybrid Consolidation Simulation System(ハイブリット圧密シミュレーションシステムの開発)

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授　与　学　位	博士（工学）
学位授与年月日	平成17年3月25日
学位授与の根拠法規	学位規則第4条第1項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）土木工学専攻
学位論文題目	Development of Hybrid Consolidation Simulation System （ハイブリッド圧密シミュレーションシステムの開発）
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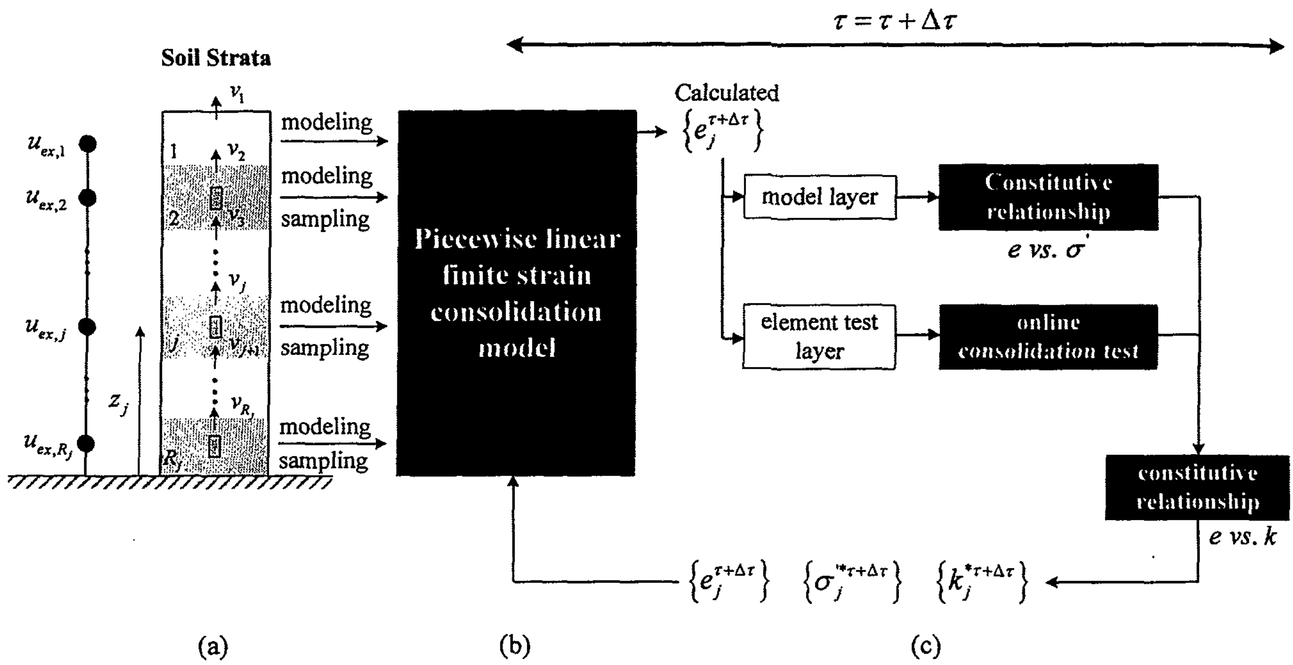
論文内容要旨

The conventional consolidation theory developed by Terzaghi in 1925 is one of the most widely applied theories in geotechnical engineering. However, the conventional one-dimensional consolidation theory developed by Terzaghi assumes an infinitesimal or zero strain condition, and the constant compressibility and hydraulic conductivity during consolidation. At present, it is widely recognized that assumptions of the conventional theory are only approximately satisfied, and the error arising from such assumptions will depend on the magnitude of the loading increment and of the void ratio changes. Actually, the compressibility and hydraulic conductivity of soft clay varies nonlinearly according to the effective stress conditions. Furthermore, these nonlinearities also have considerable variations in cases where the soils have high initial water content. The methodology, therefore, in the calculation using the conventional consolidation theory includes an unacceptable error. This error ranges from 100% to 300% in some instances. Consequently, the difficulties in the current state of art for settlement prediction originate from the difficulties both in making the evaluations, and selecting the consolidation parameters and the various deformation characteristics of the natural clay near the preconsolidation pressure. Thus, recognizing the limitations of the conventional theory, there has been a concerted effort to improve the shortcomings of the assumptions to predict the magnitude and the rate of consolidation settlement.

Base on the problem recognition, we have developed a new consolidation simulation system to introduce the nonlinear stress-strain relationship of natural soft clay more realistically to the computation of the consolidation settlement. In newly developed system, the computational body computes the change of the void ratio for the next time step and directly controls the computed volumetric strain to the specimen, as shown in Figure 1. After that, the response of the soil specimen such the change of excess pore water pressure is introduced to the governing equation repeatedly. That is, the stress-strain relationship of soil is replaced by the element tests. This is the basic concept of this study. Because the element test and the numerical model are intermingled in the multi degree of freedom problem in general, this simulation method has been called the 'hybrid simulation method'. Therefore, the main objective of this study is to develop a new consolidation simulation system including an algorithm of hybrid simulation method and the software

Figure 1 Basic procedure of hybrid consolidation simulation system



and hardware environment to overcome the two basic drawbacks of the past consolidation settlement analysis. We have named the system 'HyCoS' (Hybrid Consolidation Simulation).

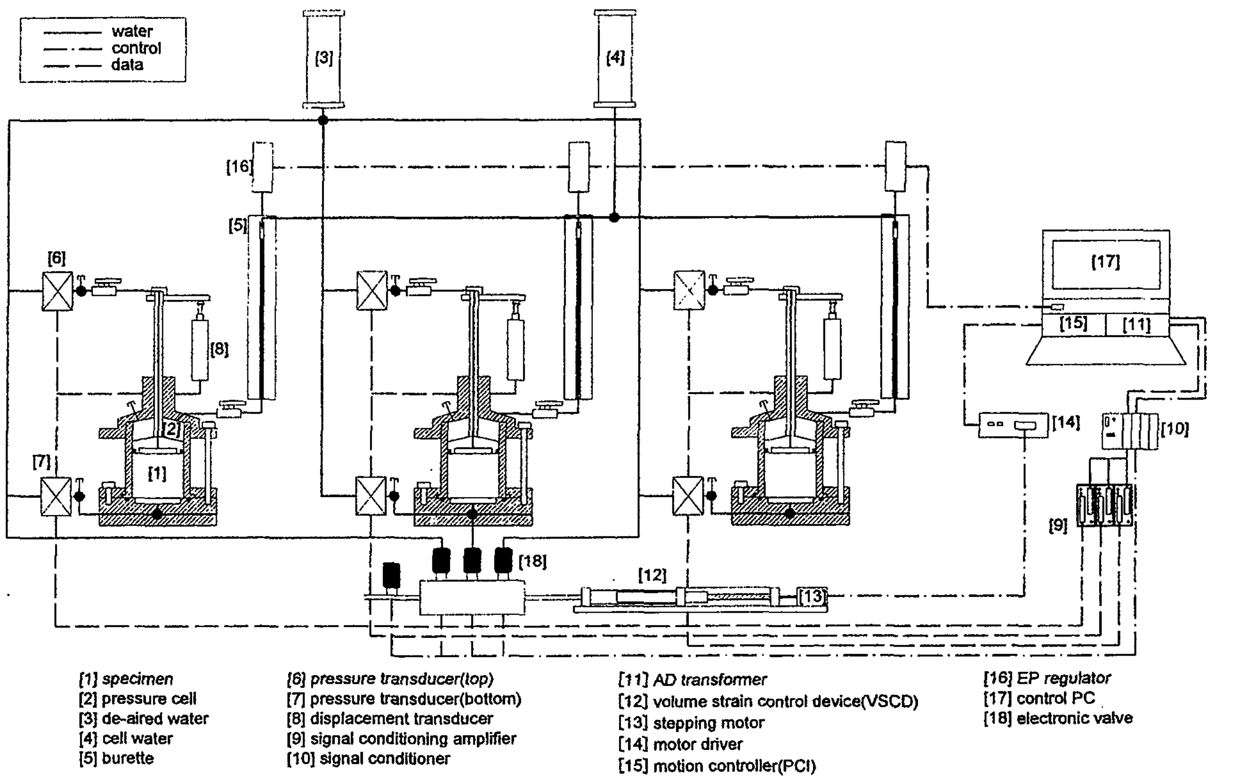
The advantages of the system HyCoS are summarized as follows: (1) a complicated evaluation and selection process of the consolidation parameters such as the coefficient of consolidation and preconsolidation settlement is not required in the system HyCoS (refer to Chapter 4.1), because the vertical effective stress conditions of the soil specimen are introduced directly to the computation body after the volumetric strain control, (2) because none of the assumptions are required to simulate the soil constitutive relationship, the consolidation analysis including various types of soil behavior and various conditions of the practical consolidation problem can be carried out easily, and (3) a delicate simulation of the consolidation behavior is possible through the infinitesimal control of the movement of pore water and the undisturbed soil specimen. Especially, it is meaningful to simulate the complicated consolidation behavior near the preconsolidation pressure.

Despite recent advances in the development of the hybrid simulation method, it is the first trial for a static geotechnical problem which includes a consolidation settlement analysis. Furthermore, we think it is the most advanced and integrated simulation method involving the techniques of soil sampling, element tests, and numerical analysis techniques. We expect that the development of this system contributes not only to the consolidation settlement problem, but to the experimental approach in geotechnical engineering field.

We carried out our research as shown below to realize the objectives of this study:

1) **Formulation of a piece-wise linear model for finite strain consolidation that is applicable to hybrid simulation (chapter 3):**

Figure 2 Hardware configuration of the system



Finite strain consolidation theory is one of the most reliable and versatile approach to simulating large deformation consolidation phenomenon, since it mainly traces the skeletons of soil which move with consolidation. To make the results attractive to practical geotechnical engineers, a piece-wise linear model for finite strain consolidation problems applicable to the hybrid simulation was formulated in this study.

2) Development of hybrid simulation system for the nonlinear properties of constitutive relationship (chapter 4):

The hybrid simulation system has been developed in order to perform a step-by-step analysis of a consolidation governing equation introducing the nonlinear response behavior or constitutive relationship from the undisturbed soil specimen in an online state. There are two major advantages of this simulation method: 1) the decision and selection process of parameters to simulate the stress-strain behavior can be skipped, 2) laboratory element tests which assumed various ground conditions can be carried out easily. If the advantages could be employed efficiently in the consolidation settlement analysis, the complicated constitutive relationship in compressibility and hydraulic conductivity, especially near preconsolidation pressure, can be considered in the coupling consolidation governing equation of the soil skeleton and pore water. Consequently, the analysis of the consolidation settlement will yield result with high accuracy (Figure 2).

3) Modifications of the ordinary cell-type consolidometer to increase the control efficiency of the system (chapter 4):

Despite the widespread use of the Rowe cell consolidometer, two major shortcomings of the system have been highlighted. Firstly, it is difficult to assemble the bellofram loading system without entrapping air or water between the bellofram and the cell wall. During consolidation, compression of the air or expulsion of the wall will lead to erroneous volume change measurements. Secondly, the force applied to the bellofram may not be fully transmitted to the specimen, causing discrepancies of as much as 15-20%. To overcome these two major shortcomings, extensive research has been carried out on possible modifications for the original arrangement of the Rowe cell. Because the hybrid consolidation system adopts infinitesimal control and the measurement of volume changes of excess pore water pressure, the original arrangement of the Rowe cell is especially hard to apply. Therefore, the cell-type consolidometer used in this study was originally designed on the basis of modifications to the original Rowe cell consolidometer.

4) **Development of software for the controls and measurements (chapter 4):**
Because repetitive computation-control-data acquisition is carried out over a long time for testing in the hybrid consolidation system, an automation of these three processes is an indispensable element for the development of the system. For the automation of computation, control and measurement, the program HyCoS is originally developed on the basis of a LabVIEW-based environment.

After the development of the system HyCoS, we carried out carried out several laboratory illustrative simulation problems and the comparative research using the field monitoring data measured from Murayama test embankment in order to verify the system. In laboratory simulation, we carried out verifications of the operational stability of the consolidometer, the VSCD, and the control and data acquisition system during the CONPERM test. The system showed good performance with regard to the generation of pressure, the control of the movement of pore pressure during saturation, consolidation, and the hydraulic conductivity test for long periods of testing. The system HyCoS reproduced the consolidation behavior of fully remolded Kaolinite in the magnitude and the rate of the consolidation settlement. The verification of the applicability of the system to a practical consolidation settlement problem was also carried out. Undisturbed field specimens and field monitoring data obtained from Murayama test embankment constructed by Japan Highway Public Corporation was used for the comparative study. We concluded that there were no serious discrepancies between the system HyCoS simulation and the field monitoring data in the magnitude of the consolidation settlement and the dissipation of the excess pore pressure during consolidation process

In our fundamental study of the development of the hybrid consolidation simulation system, we described here the developmental process and system component. In order to simplify the development, we focused to the stress-strain relationship of the compressible soil and the primary consolidation settlement caused by the dissipation of excess pore water pressure. However, in order to increase the eligibility of the system HyCoS, we have to improve the system to consider the secondary consolidation of soft clay, and to estimate the hydraulic conductivity directly from undisturbed specimens during hybrid simulation. Furthermore, two research subjects are recommended to enlarge the applicability of the system HyCoS. One is to develop a system for a delayed consolidation behavior simulation of the highly structure quasi-overconsolidated clay. The other is to work on a way to predict the magnitude and the rate of the consolidation settlement of the dredging and the municipal landfill

論文審査結果の要旨

軟弱粘性土地盤上に建設される海上空港やウォーターフロント開発のためには、軟弱粘性土地盤の圧密沈下過程を高精度に予測する必要がある。本論文は、原位置の粘土試料を用いて、高精度に沈下を予測するための新しいハイブリッド圧密シミュレーションシステムの開発に関するものである。

第1章は、研究の背景と目的を述べ、ここで開発するシステムの必要性・優位性を述べている。

第2章は、本論文に関係する既往の研究を整理している。

第3章では、開発したシステムの数値解析環境を説明している。数値解析は、有限変形理論に基づいて定式化され、微小変形理論の枠組みでは取り扱うことの困難な大変形問題を対象にすることを可能としている。圧密実験を伴わない数値計算のみの条件下でも、任意の構成関係、すなわち有効応力−体積比関係、有効応力−透水係数関係を規定することによって、シミュレーションが可能なシステムとなっている。システムは、圧密沈下予測実務に直ちに利用できる実用性を有している。

第4章では、開発したシステムの圧密試験部分のハードウエア要素試験環境を説明している。粘土供試体に所定の荷重を高精度に作用させる新たな圧密容器、および粘土からの排水を高精度に制御できる体積ひずみ制御装置を新たに開発した。また、電磁弁の制御によって、複数の圧密試験機を1台のＰＣでコントロールするなど、将来的な汎用性を視野に入れた最大限の制御計測環境を実現している。これらは、従来の圧密試験装置では実現し得ないハードウエア環境を提供している重要な成果である。

第5章では、開発したシステムの動作を、体積変形が微小な場合と大きな変形の場合について、理論解と比較し、高精度のシミュレーションが可能であることを確認している。このような要素実験と数値解析をハイブリッドに組合せた実用的な圧密沈下シミュレーションシステムは世界的にも類例が無く、先端技術の実用化に先鞭をつけたものとして価値がある。

第6章では、開発したシステムを、実際の圧密問題に適用した事例について述べている。対象とした問題は、山形県村山市で建設中の高速道路試験盛土の沈下解析である。解析の結果、地盤のせん断変形を除いた体積変形は、開発したシステムによって十分な精度でシミュレーション可能であることを示した。

第7章は、本研究の結論および今後の展望について述べている。

以上、本論文は圧密沈下過程を、現場の粘土試料を用いて数理的な材料構成モデルに頼らずに、直接的に実験から予測する新たなハイブリッド圧密実験システムを開発したものである。この手法は、超軟弱粘土やセメンテーションの発達した地盤など、構成モデルの設定が困難な地盤の圧密沈下予測に適用可能な手法であり、地盤工学分野の発展に寄与するところが少なくない。

よって、本論文は博士(工学)の学位論文として合格と認める。