한국지반환경공학회 논문집 제7권 제1호 2006년 2월 pp. 67~80

Fundamental Aspects of Hybrid-Online Simulation for One Dimensional Consolidation Analysis

Hybrid-Online 방법을 통한 압밀해석

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Abstract

This paper presented an application of the geotechnical hybrid-online simulation to the consolidation settlement problem of soft clay. Conventional numerical analyses have used idealized soil constitutive models obtained from the laboratory soil tests. On the other hand, in the hybrid-online simulation, soil response was directly introduced to numerical analyses from the soil element test, and, therefore, the complicated parameter estimation was not required in this method. Fundamentals of the hybrid-online simulation method and the development of the algorithm and corresponding hardware and software for the system were presented in this study. Furthermore, an incremental loading consolidation and the hydraulic conductivity test and a comparative study using the Terzagh's conventional consolidation theory were carried out for the system verification including the performance of the experimental device and source coding of software components, and the data reliability obtained from the system. In conclusion, we found that the hybrid-online consolidation simulation system could reproduce the consolidation behavior of the remolded Kaolinite specimen withoutany discrepancies.

Keywords : Hybrid-Online simulation method, Consolidation settlement analysis, Soft soil, Nonlinear coefficient of consolidation

요 지

본 논문에서는 지반 하이브리드-온라인 시뮬레이션의 방법을 압밀 해석에 적용하기 위한 시도를 수행하였다. 일반적인 수치해석법이 실내시험을 통해 얻어진 흙의 구성모델을 이상화시켜 사용하는 것과 달리, 이 방법에서는 흙의 거동을 요소시험체로부터 직접 도입해가면서 해석을 수행한다. 그러므로 복잡한 파라미터의 평가과정이 생략될 수 있게 되며 인위적 이상화에 의한 해석 오차를 경감할 수 있게 된다. 본 논문에서는 실험장치의 물리적 성능을 검증하기 위하여 단계압밀시험과 투수시험(CONPERM test)을 수행하여 제어와 계측의 결과를 고찰하였으며, 시스템으로부터 얻은 데이터의 건전성을 평가하기 위하여 검증해석을 수행하였다. 결과적으로, 본 연구를 통해 개발된 하이브리드-온라인 압밀해석 시스템은 재성형된 카오리나이트의 압밀거동을 모순없이 재현하고 있음을 알 수 있었다.

주요어 : 하이브리드-온라인 시뮬레이션, 압밀침하해석, 연약층, 비선형압밀계수

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1. INTRODUCTION

Because of defective engineering properties of soft soil such as high compressibility and low shear strength, the utilizations of area with these type of soils as construction sites has been avoided. However, the population increase and the expansion of an economical scale require all kinds of land to be used for the construction of infrastructure, waterfront development, and land reclamations. Because of these demands, there has been an increase in construction work on engineering disadvantageous soft soil, and offshore reclamations in recent year. When constructing the structure on this soft clay, the consolidation settlement of compressible layer is a fundamental data in order to compute the design efficiency of structures constructed on the soft clay and to select countermeasures. Especially, the magnitudes and rates of the consolidation settlement have been became a major interest for the geotechnical engineers.

The conventional consolidation theory developed by Terzaghi in 1925 is one of the most widely applied theories in geotechnical engineering. More than 80 years after it was first developed, it is still taught to virtually every geotechnical engineering students, and is still used by virtually every practicing geotechnical engineers, even though there are more advance methods are also taught and used from time to time (Bjerrum, 1973; Duncan, 1993; Alfredo et al., 2002). However, the conventional one dimensional consolidation theory developed by Terzaghi assumes an infinitesimal or zero strain condition, and the constant compressibility and a hydraulic conductivity during the 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. Especially, the soil constitutive relations for the consolidation analysis still being debated even at present despite the one dimensional consolidation theories have been greatly advanced until now.

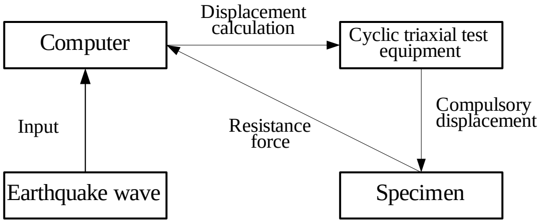


Figure 1. Block diagram of online real time test

Therefore, author has paid attention to the hybrid-online simulation method to develop a new simulation system to introduce nonlinear stress strain relationship of natural soft clay more realistically for the computation of the consolidation settlement (Kwon and Kazama, 2003; Kwon, 2005). In this paper, the reviews and

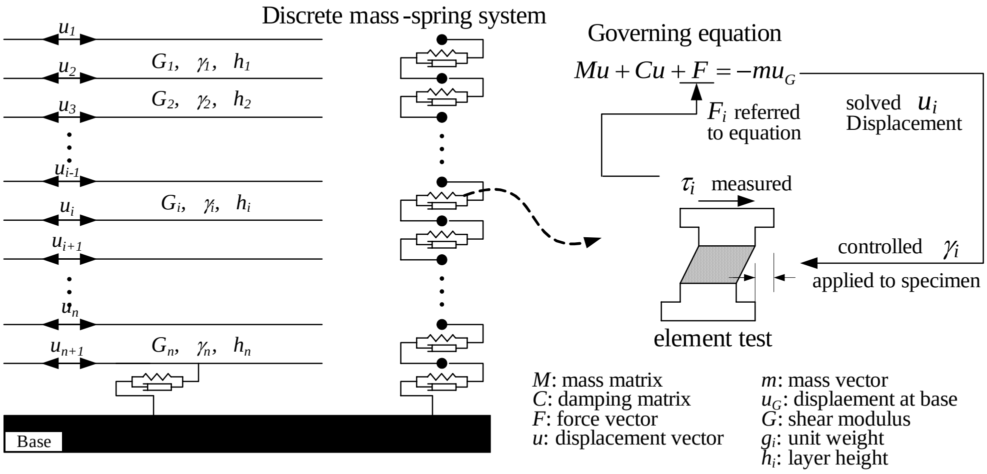


Figure 2. Outline of hybrid seismic simulation developed Sento et al. (2002)

reconsiderations on the hybrid-online simulation method, the applicability of the method to the nonlinear consolidation settlement analysis, the development of the algorithms and experimental devices, and the verification of the system were presented.

2. FUNDAMENTALS OF THE HYBRID-ONLINE SIMULATION METHOD

Hakuno and Shidawara(1969) proposed the basic concept of the hybrid-online simulation method for the first time. They researched the nonlinear property of the resistance force of the beam subjected to seismic external force. In general, when performing nonlinear earthquake response analysis of structure in the plastic region, the vibration equation will be solved step by step in a time domain. That is, if deformation at a certain moment is decided, the corresponding resistance force can be calculated from the constitutive model. However, they proposed that the resistance force property could be obtained from element tests instead of a constitutive model. That is to say, if deformation is developed in structure at a certain moment during an earthquake, the resistance force can be measured after giving the corresponding strain to the specimen. The numerical solution for next time step can then be calculated from these measured values. Therefore, by repeating this process in the time domain, the analysis can proceed without a constitutive model as illustrated in Figure 1 (Katada and Hakuno, 1982; 1984).

Because the experimental equipment should be controlled in online, it has been called the “online test”. Since this method has been developed, it has been mainly applied in the structural engineering field. In some cases, only a part of degree of freedom(DOF) was replaced by the element test, since it was difficult to obtain resistance force properties from all DOF in multi DOF system. Because the numerical model and element test are intermingled in such a case, it is called the "hybrid-online simulation method" or the "substructure online simulation method".

Recently, Yamaguchi et al. (2002) explained that the liquefaction phenomenon of reclaimed deposits highly related to the rigidity of sub clay layer with the hybrid-online simulation system using Kobe Port Island liquefaction data. Sento et al. (2002, 2004) and Kazama et al. (2004) developed the hybrid-online simulation system to predict the seismic behavior of sand during liquefaction considering pore water migration (Figure 2).

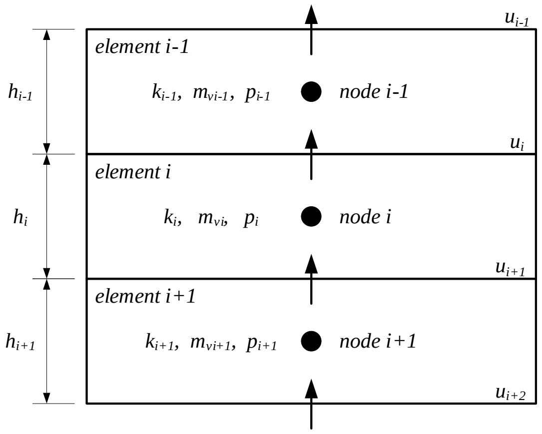


Figure 3. Movement of pore water between contiguous elements

The hybrid-online simulation method has mainly been used for seismic response analysis of the soil up to present. Recently, there have been more application cases for the prediction of liquefaction damage, and this method has become a general technique in dynamic geotechnical engineering field.

3. HYBRID-ONLINE SIMULATION FOR THE CONSOLIDATION SETTLEMENT ANALYSIS

As the first trial for the development of the system, we approached to the horizontally multi layered consolidation problem on the basis of assumptions as following; 1) infinitesimal strain, 2) no time effect on deformation, 3) both soil skeleton and pore water are incompressible, and deformation and flow are occurred in one dimensional, 4) a soil layer is homogeneous in multi layered system, 5) Darcy's law is valid, and 6) the logarithm of the hydraulic conductivity is assumed to vary linearly with the void ratio.

3.1 Governing equation

The continuity equation of the saturated soil by the flow of the pore water between contiguous elements as illustrated in Figure 3 is expressed

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{\partial v}{\partial z} \tag{1}$$

where, ε_v is the vertical volume strain, v is the flow velocity, t is the time and z is the vertical coordinate. Then, by Darcy's law, Eq. (1) can be rewritten as

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{\partial}{\partial z}\left(\frac{k}{\gamma_w}\left(\frac{\partial p}{\partial z}\right)\right) \tag{2}$$

where, k is the hydraulic conductivity, p is the excess pore pressure, and γ_w is the unit weight of pore water.

The relationship between the variation of vertical effective stress and the variation of vertical strain, that is, the constitutive relation is

$$d\varepsilon_v = m_v d\sigma_z' \tag{3}$$

where, σ_z' is the vertical effective stress and m_v is the coefficient of volume change. Since there are no changes of total stress with time, Eq. (3) can be rewritten as,

$$d\varepsilon_v = -m_v dp \tag{4}$$

The governing equation for the conventional one dimensional theory can be obtained from Eq. (2) and Eq. (4).

3.2 Discretization of governing equation

First of all, the spatial discretization of governing equation is assumed as shown in Figure 3. Spatial discretization is conducted with the explicit difference method. Considering the flow of pore water and displacement of i th element, Eq. (2) can be discretized as

$$\begin{aligned}\dot{u}_i - \dot{u}_{i+1} &= -\frac{\bar{k}_i}{\gamma_w}\cdot\frac{p_{i-1}-p_i}{\frac{h_{i-1}+h_i}{2}} + \frac{\bar{k}_{i+1}}{\gamma_w}\cdot\frac{p_i-p_{i+1}}{\frac{h_i+h_{i+1}}{2}} \\ &= -\left(\frac{\bar{k}_i}{\gamma_w}\frac{2}{h_{i-1}+h_i}\right)p_{i-1} + \left(\frac{\bar{k}_i}{\gamma_w}\frac{2}{h_{i-1}+h_i} + \frac{\bar{k}_{i+1}}{\gamma_w}\frac{2}{h_i+h_{i+1}}\right)p_i \\ &\quad -\left(\frac{\bar{k}_{i+1}}{\gamma_w}\frac{2}{h_i+h_{i+1}}\right)p_{i+1}\end{aligned} \tag{5}$$

where, $\dot{u}_i$ is the displacement velocity, h_i is the thickness of layer, p_i is the excess pore water pressure of i th element. $\bar{k}_i$ is the average hydraulic conductivity between i th and $i-1$ th element, and defined as followings,

$$\bar{k}_i = \frac{k_i k_{i+1}}{k_i h_{i-1} + k_{i-1} h_i}\left(h_i + h_{i-1}\right) \tag{6}$$

And then, considering the upper and lower boundary of i th element, the equilibrium of the element can be expressed as

$$T_{u(i)} = p_i + \varepsilon_{v(i)}/m_{v(i)} = p_i + \alpha_i\left(u_i - u_{i-1}\right) \tag{7}$$

$$T_{u(i)} = -\left(p_i + \varepsilon_{v(i)}/m_{v(i)}\right) = -p_i - \alpha_i\left(u_i - u_{i-1}\right) \tag{8}$$

where, T_i is the downward force acting on the boundaries and α_i is the value related to the reciprocal of the coefficient of volume change and the layer thickness. We can obtain the discretized equation in the time domain by using Eqs. (5)~(8).

Eq. (1), the so called continuity equation expresses the relationship between the change in soil volume and the change in soil voids, assuming the incompressibility of the soil grain and pore water. To solve the continuity equation through a difference method requires either implicit or explicit solution methods. An implicit difference scheme has usually been adopted for various purposes up to present since a relatively stable and accurate solution can be obtained by this method. Unlike the implicit solution scheme, which is unconditionally stable for large time steps, the explicit scheme is stable only if the time step size is smaller than the critical time step size for the structure being simulated. Furthermore, in a convergence computation using implicit difference scheme with the predictor and the corrector, the iteration computation inevitably obtains a solution for a certain time step. This implies that the computed displacement should be generated repeatedly to the soil specimen until the convergence computation is finished. Therefore, the implicit scheme cannot be applied to the hybrid-online simulation method. The solution can be obtained using just a computation process through the explicit difference scheme. It is essential that the response of the soil specimen is introduced from the experimental equipment through just one time of control. In this study, the explicit difference scheme was used for the discretization of the governing equation considering pore water flow. From Eq. (5), the displacement vector for the next time step can be expressed as

$$\left\{u_i^{j+1}\right\} = \left\{u_i^j\right\} + \Delta t\left[A\right]^{-1}\left[\bar{k}_i^{\,j}\right]\left\{p_i^j\right\} \tag{9}$$

where, $\left\{u_i^j\right\}$ is the displacement vector, $\left\{p_i^j\right\}$ is the excess pore water pressure vector, $\left[\bar{k}_i^{\,j}\right]$ is the average hydraulic conductivity matrix for the i th element and $[A]$ is coefficient matrix. On the other hand, the equilibrium equation can be written from Eqs. (7) and (8)

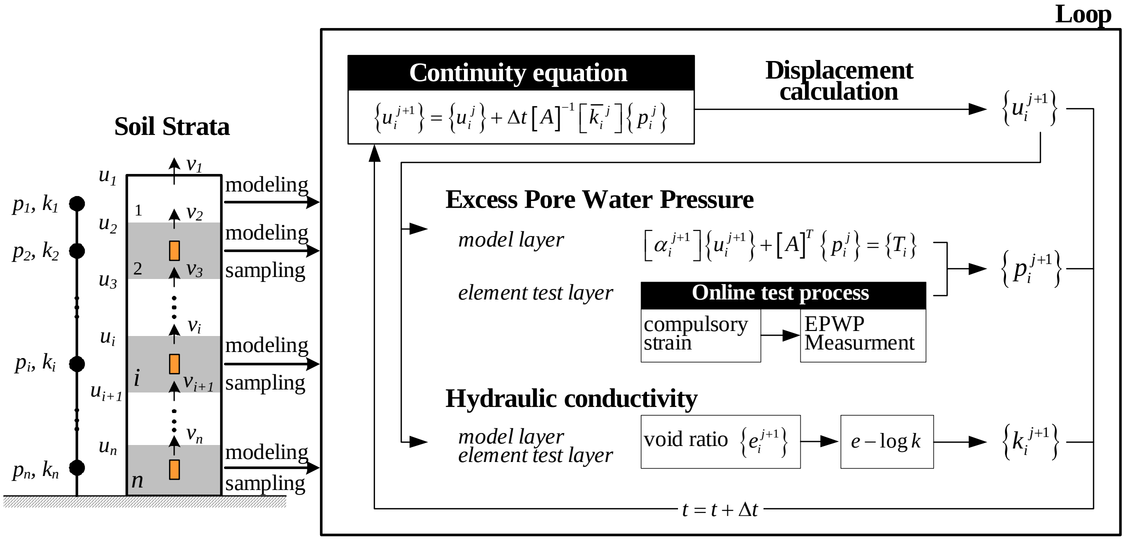
$$\left[\alpha_i^{j+1}\right]\left\{u_i^{j+1}\right\} + \left[A\right]^T\left\{p_i^j\right\} = \left\{T_i\right\} \tag{10}$$

where, $[\alpha_i^j]$ is the matrix of the reciprocal of the coefficient of volume change. $\{T_i\}$ is the downward force vector acting on the boundaries.

3.3 Basic procedure of the hybrid-online simulation for the consolidation settlement analysis

Figure 4 shows the basic procedure of the hybrid-online consolidation simulation. A spatial discretization was taken into consideration, as shown in Figure 4(a). The discretized nodes remained at the center of their respective elements throughout the consolidation process and print out information such as excess pore water pressure, the void ratio and the hydraulic conductivity during the consolidation. In the element test layer, the undisturbed soil specimen should be prepared for the element test. The undisturbed field samples were essential in the hybrid-online simulation since it was performed under a reproduced in-situ vertical effective stress state.

After finishing the numerical modeling of the multi layered soil, the displacement vector for the next time step $j+1$, $\left\{u_i^{j+1}\right\}$ could be calculated using Eq. (9) under the various specified analysis conditions: the initial and boundary condition, the loading condition, and the material property of each compressible layer. And then, the hybrid-online



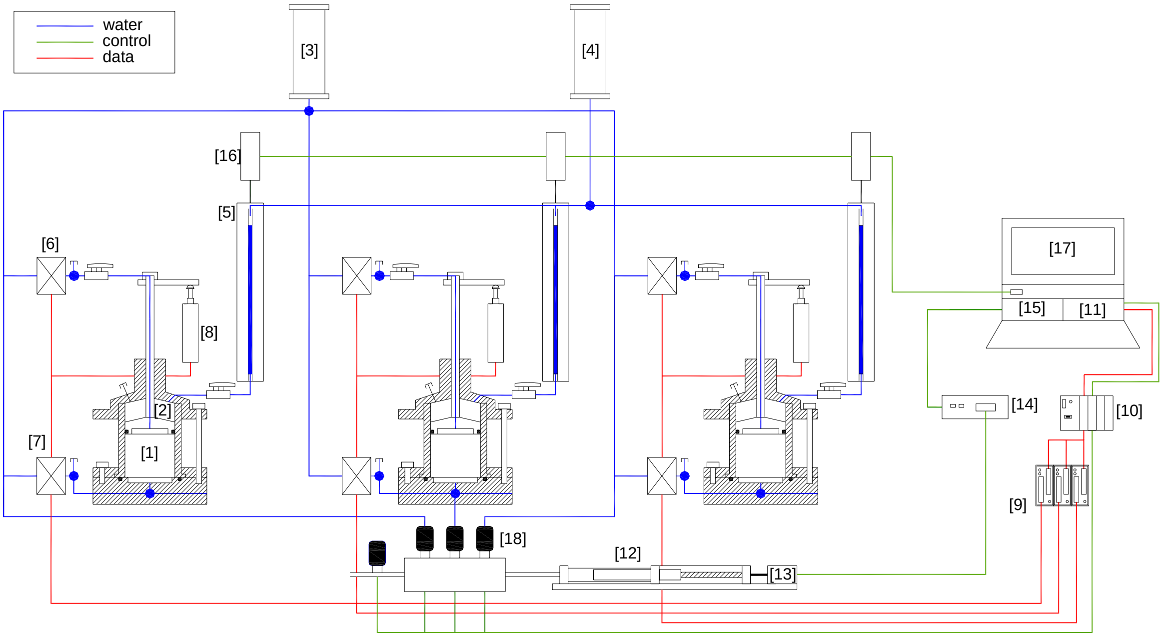
(a) (b)

Figure 4. Basic procedure of consolidation analysis by using the hybrid-online simulation method

simulation was begun. In the model layer, the excess pore water pressure for the next time step was obtained from the predetermined constitutive model of the compressibility using Eq. (10). On the contrary, in the case of the element test layer, pore water pressure was measured after generating the computed volumetric strain to thesoil specimen in online state (online test). From measured and computed excess pore water pressure, the excess pore water pressure vector for the next time step, $\{p_i^{j+1}\}$ was reassembled. For the next process, the computation of the hydraulic conductivity was carried out. Theoretically, there was no problem in measuring the hydraulic conductivity directly for a certain void ratio state of soil. However, two disadvantages were considered in such cases. One was the disturbance of soil specimen. To obtain a stable solution using the explicit difference scheme, a small time increment was applied for the computation of the consolidation settlement. If we conducted the hydraulic conductivity test for each time step, the disturbance of soil specimen affected a significant influence to the experimental results. Another problem was related to the testing time. Each of the time steps required a long operational time for the test, since the hydraulic conductivity test required a considerable time to reach the static state in general. In addition, because of the fact that the relationship between the void ratio and the logarithm of hydraulic conductivity is represents the behavior of most natural soft clay well, it has been commonly accepted (Mesri and Rokhar, 1974; Tavenas et al., 1983). Because of these, the hydraulic conductivity is estimated using an assigned relationship, not directly measured value from the specimen, even in the element test layer. Therefore, the relationship between the void ratio and the hydraulic conductivity should be prepared before the beginning of the hybrid-online simulation, and the hydraulic conductivity vector for the next time step is estimated using the relationship both in the model layer and in the element testing layer as illustrated in Figure 4(b).

Settlement analysis could be advanced with the substitution of some or all elements in this system by repeating the above mentioned procedure until the analysis satisfied the termination criterion of the degree of saturation or an elapsed time. This is basic to the concept and procedure of the hybrid-online consolidation simulation system.

Consequently, the nonlinear stress strain behavior of soft soil can be directly introduced from the soil specimen in this system. Therefore,



[1] specimen
[2] pressure cell
[3] de-aired water
[4] cell water
[5] burette

[6] pressure transducer(top)
[7] pressure transducer(bottom)
[8] displacement transducer
[9] signal conditioning amplifier
[10] signal conditioner

[11] AD transformer
[12] volume strain control device(VSCD)
[13] stepping motor
[14] motor driver
[15] motion controller(PCI)

[16] EP regulator
[17] control PC
[18] electronic valve

Figure 5. Hardware configuration of the system

it is not required to estimate the consolidation parameters, nor is the selection processes for the simulation of stress strain behavior of compressible soil necessary. As a result, the possibility of erroneous factors in these processes was reduced considerably.

4. SYSTEM CONFIGURATIONS

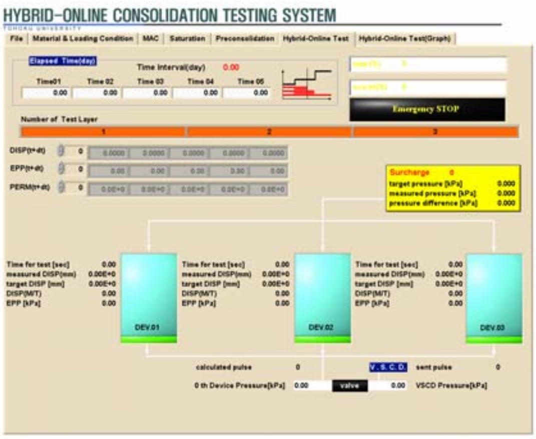
To establish the hybrid-online simulation system for the consolidation analysis, the hardware and software (including computational body) should be connected and controlled in an online state.

4.1 Hardware configuration

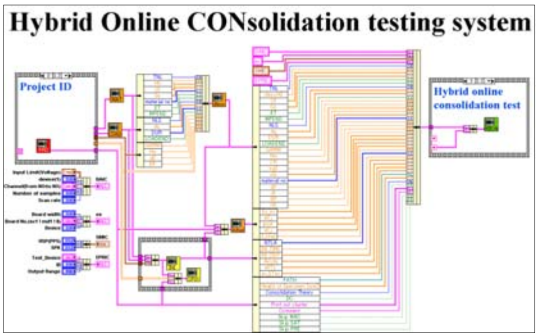
Figure 5 shows the configuration of experimental equipment of the hybrid-online consolidation system. The system divided into three major parts, 1) cell type consolidometer and transducer, 2) volume strain control device, 3) control and data acquisition device. The system was made on the basis of PC controlled automation.

Cell type consolidometer consists of the consolidation cell, the loading plate and the transducer. Despite the widespread use of the originally Rowe cell, shortcomings of the system such as entrapping air or water between bellofram and the cell wall and discrepancy in force transmission have also been highlighted (Khan and Garga, 1994; Premchitt, et al., 1996; Blewett, et al., 2002) . Therefore, we designed the cell type consolidometer through modifying Rowe cell consolidometer to improve volumetric strain control accuracy. The consolidation cell has a dimension with an inner diameter of 60mm, an outer diameter of 77mm and a height of 55mm. In order to investigate highly compressive soil, maximum height of specimen is set to 55mm.

In addition, one of the most important factors in developing the system is to generate the calculated displacement (volumetric strain) to specimen



(a) Interface configuration of main subroutine HBON.vi



(b) Source code of HOCON

Figure 6. Program HOCON

accurately. Therefore, a volumetric strain control device (VSCD) was originally developed and used in this study. By using the VSCD described here, we had the ability to control the volume change and pore water transport processes in the soil specimen. The capabilities include the measurement of equipment compliance, the constant rate of deformation, the consolidation, and very small strain compression, the hydraulic conductivity, the strain path control test combining with other test equipment. This equipment consists of stepping motor, piston, pore water cell and driving rail, and performs inflow and an outflow of pore water with the piston connected to the stepping motor. The resolution of the stepping motor was 0.036°/pulse, and the lead length of the precision piston table was 2mm. From these data, it was found that the resolution of VSCD is $6.3\times10^{-5}cm^3$/pulse. Considering this resolution, the experimental equipment of the system could be used to control the infinitesimal strain. Finally, when using low permeable materials, it takes a long operational time to conduct the consolidation test. In order for the system to have the maximum efficiency, then, the experimental equipment should be automated.

4.2 Software Components

Because repetitive computation control data acquisition was carried out over a long time for testing in the hybrid-online simulation, an automation of these processes was an indispensable for the development of the system. We developed a program HOCON to perform these tasks. The program has six major subroutine; 1) input data, 2) operational state certification procedure, 3) initial computation, 4) saturation, 5) preconsolidation procedure, and 6) hybrid-online simulation process. Through the successive execution of these six procedures, the hybrid-online simulation for the nonlinear consolidation settlement analysis was carried out. Programming of source code was carried out using LabVIEW 6.1 manufactured by National Instrument Co., LTD. Figure 6 shows an interface configuration and a source code of the main program HOCON.

The relationship between the void ratio and the hydraulic conductivity is an essential input data both in the model layer and in the element test layer. To obtain the vertical effective stress - void ratio - hydraulic conductivity relations of compressible clay soils, we also developed a computer program CONPERM.

5. EXPERIMENTAL PROCEDURE

(1) To prepare the constitutive relations of the compressibility and the hydraulic conductivity, incremental loading (IL) consolidation test and the hydraulic conductivity test were carried out using program CONPER.

(2) After the installation of the specimen, all

valves, the hollow drain spindle and the pressure cell were filled with de aired water.

(3) Analysis conditions and parameters were assigned.

(4) Backpressure of 200kPa was generated using VSCD and EP transducers during at least 24 hrs to increase the degree of saturation of specimen.

(5) The initial vertical effective stress obtained from the initial computation was applied to the undisturbed soil specimen to reproduce the initial condition of stress.

(6) Online simulation: the number of pulse was computed from the target value of volumetric strain (1pulse = $6.3\times10^{-5}cm^3$), and the stepping motor was controlled with a strain rate of 0.0069%/min or a slower rate. If there was no rise in the pore water pressure, and then excess pore water pressure for the computation of the next time step was measured. The vector of excess pore water pressure was reassembled with the computed values of model layer and the measured values of element test layer. Also, the vector of the hydraulic conductivity was reassembled using the relationship between the void ratio and the hydraulic conductivity.

(7) Finally, the simulation loop was repeated until satisfying the termination criterion.

6. ILLUSTRATIVE SIMULATION FOR THE SYSTEM VERIFICAITION

To verify the operational stability including hardware and program coding, and the reliability of the data obtained from the developed system, an illustrative simulation was carried out using a fully reconstituted specimen. AA Kaolinite with a grain size distribution of $2\mu \sim 5\mu$ was used for this illustrative simulation.

6.1 Specimen preparation

The physical properties of AA Kaolinite are a specific weight of 2.714, and a pH of 3.9. The liquid limit and plastic limit is 47.62% and 32.7%, respectively. To prepare a remolded specimen, oven dried Kaolinite was mixed with de aired water at water content of 71.43%, i.e., 1.5 times the liquid limit. After 24 hours of the de airing process, the slurry state mixture was put into a consolidation mold with a height of 20cm and a diameter of 10cm. The testing specimens were obtained by subjecting the mixture to a series of static dead loads until the final consolidation pressure reached 98kPa using a double drain condition.

6.2 Incremental loading consolidation test and the hydraulic conductivity test

To obtain the properties of the compressibility and the hydraulic conductivity of remolded clay, the incremental loading consolidation and the hydraulic conductivity tests were conducted with eight loading stages and loading increment of 25kPa using CONPERM program. Figure 7 shows the schematic diagram of the pressure control during the CONPERM test. To investigate the performance of the control and data acquisition devices, pressure and displacement data was analyzed in each experimental step.

Figure 8 illustrates the variation in the specimen height and the pressure at the top and bottom of the specimen during the saturation process of twenty four hours. As can be seen in the figure, the system generated and maintained the target backpressure of 200kPa during the whole period of the process, despite the approximately 1% range of erroneous pressure was observed. Also, the specimen height maintained an initial height of specimen

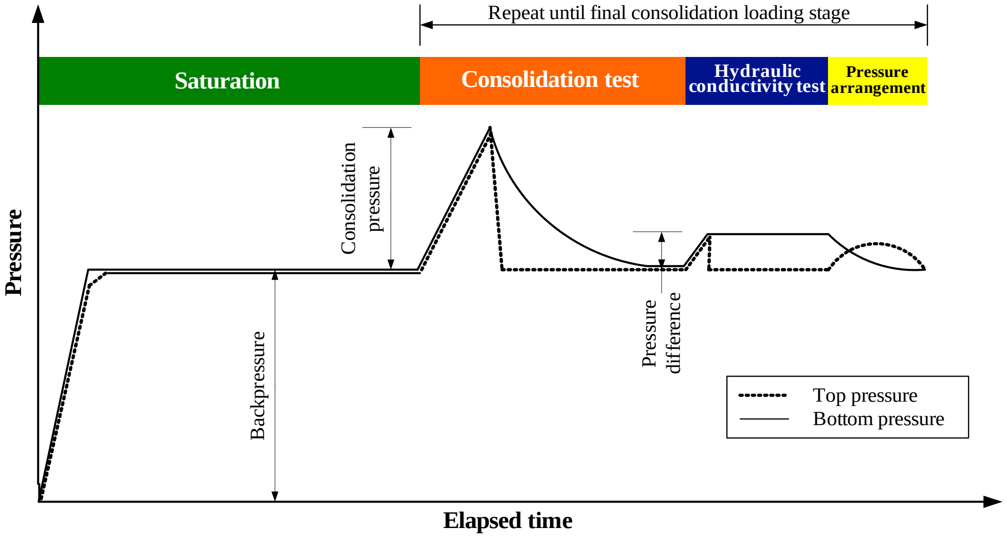


Figure 7. Schematic diagram of the pressure control during CONPERM test

during overall saturation process. By these results, we can assume that the system provided good control of the VSCD and the EP transducer during this process.

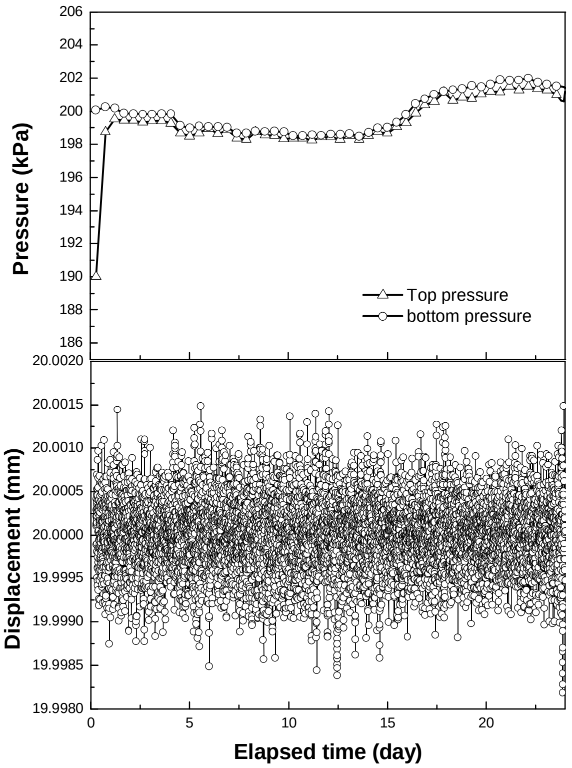


Figure 8. Variation of the specimen height and pressure during the saturation process

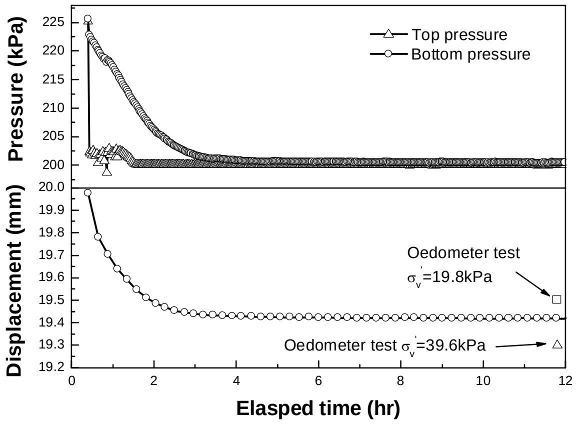


Figure 9. Example of the pressure control and corresponding displacement during the consolidation process

After the specified duration of the saturation, the consolidation test was commenced. The system controlled the VSCD to maintain the toppressure as same as the backpressure after applying a step consolidation loading. Figure 9 depicts an example of the pressure control and corresponding displacement during the consolidation pressure. Judging from figure, the specimen was controlled properly, and sufficient displacement was generated during the consolidation process.

The hydraulic conductivity of each consolidation stage was measured directly under the assigned hydraulic gradient. The maintenances of the

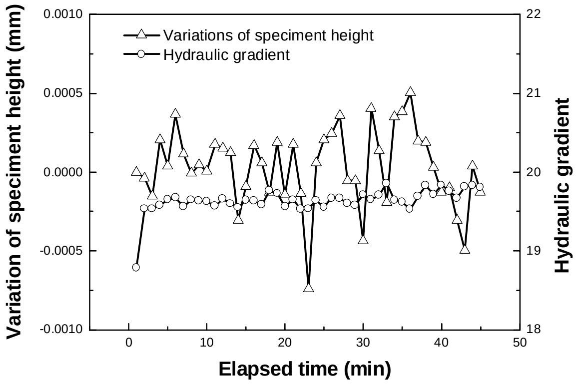


Figure 10. Measured hydraulic gradient and variation of specimen height during the hydraulic conductivity test

specimen height and the hydraulic gradient were strictly required during the measurement of the hydraulic conductivity. If the specimen height changes during this process, it affects to the variation of the void ratio of the specimen, and as a result, the constitutive relation in the hydraulic conductivity, that is, the relationship between the void ratio versus the hydraulic conductivity is affected by the change of the specimen height. However, since some amount of change is inevitable during this process, it is better to conduct the hydraulic conductivity test with the minimum hydraulic gradient which can generate a pore water flow. A range of hydraulic gradient of 10 to 30 was generally employed in this study. Figure 10 shows the measured hydraulic gradient and the corresponding displacement of specimen during an hour of the hydraulic conductivity test. In this illustrative simulation, a hydraulic gradient of 20 was selected to measure the hydraulic conductivity. From Figure 10, the system maintained good control in the generation of hydraulic gradient. In addition, the variation of the displacement reached only 0.02% of the specimen height while measuring the hydraulic conductivity. It was considered small enough to be ignored. Considering these two points, the hydraulic conductivity could be measured without any discrepancies.

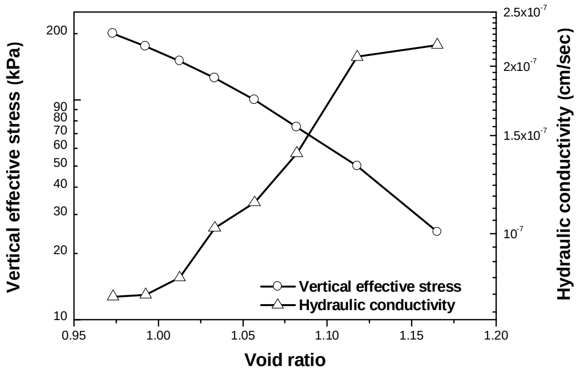


Figure 11. Soil constitutive relations for the illustrative simulation

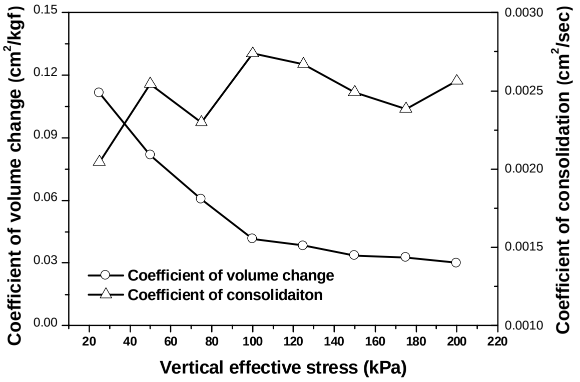


Figure 12. Consolidation parameter of fully reconstituted specimen

6.3 Illustrative simulation for the system verification

Figure 11 illustrates the result of the CONPERM test fully reconstituted Kaolinite specimen under the pressure of 98kPa. We obtained two soil constitutive relations: (a) the compressibility, and (b) the hydraulic conductivity. The hydraulic conductivity in Figure 11 is the average value of the 45 data for each loading step. And, as shown in Figure 11, there is no clear inflection point in the stress strain curve. This is because the specimen was fully reconstituted. However, we could obtain a good representation of the behavior of the relationship between the void ratio and logarithm of the hydraulic conductivity.

Figure 12 shows the variations of the coefficient of volume change and the coefficient of consolidation with a vertical effective stress. It illustrates that there are no serious the variations in the coefficient of consolidation during the consolidation.

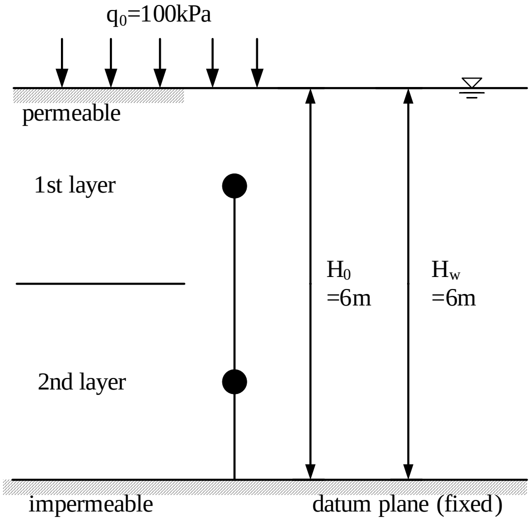


Figure 13. Geometry and initial condition for the illustrative simulation

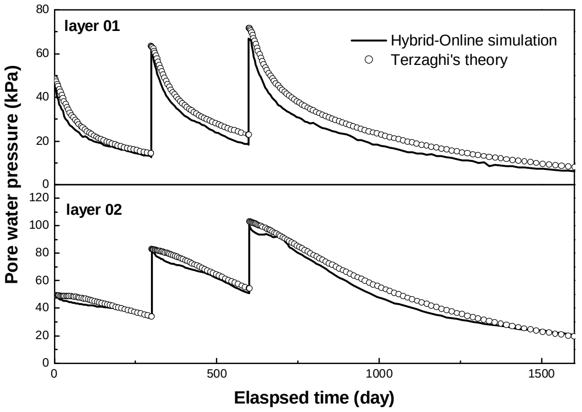


Figure 14. Comparison of the dissipation of excess pore water pressure

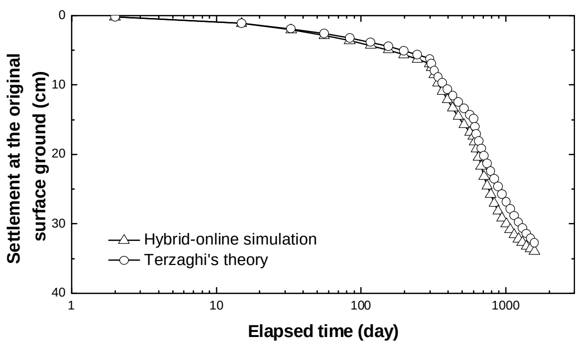


Figure 15. Time versus settlement curve

Therefore, the result of the hybrid-online simulation can be compared with the conventional one dimensional consolidation theory, which assumed the constant compressibility and the hydraulic conductivity. The obtained relationship between the void ratio and the hydraulic conductivity was used as the input parameter for the hybrid-online online consolidation simulation.

Figure 13 depicts the geometry and loading condition for the illustrative simulation. Homogenous and horizontal double layered compressible clay layer with a total height of 6m was considered. The compressible layer was subjected to an initial vertical effective stress of 100kPa and fully consolidated by the initial stress. Consolidation pressure was applied at 0 day, 300 days and 600 days with an increment of 50kPa, and the simulation was carried out with the total consolidation duration of 1600 days. The top boundary single drain condition was employed for the analysis, and the groundwater level was consistent with the ground surface as shown in Figure 13. The discretized Terzaghi's one dimensional consolidation governing equation was employed to constitute the numerical analysis body, and the stress strain relation was introduced from the specimen directly. Finally, the simulation was conducted with only element testing layers to eliminate the effect of model layer.

The conventional analysis was carried out to make a comparison with the results of the hybrid-online simulation. The average value of the compressibility and the hydraulic conductivity within the vertical effective stress range was used for the analysis, and these were maintained constantly during the consolidation. Figure 14 illustrates the comparison of the dissipation of excess pore water pressure obtained by the hybrid-online simulation and Terzaghi's theory. As known from the figures, the hybrid-online simulation shows similar behavior with the conventional consolidation theory in terms of the dissipation of the excess pore water pressure except the early stage of the consolidation, which was faster in the hybrid-online simulation than in the conventional consolidation analysis. In addition, Figure 15 indicates that the rate of the consolidation settlement is faster and the magnitude of settlement is larger for the hybrid-online consolidation testing system than the linear conventional consolidation analysis. It took about 150hrs to finish the illustrative simulation including the saturation process. During the testing, the system showed a stable performance. Furthermore, judging from Figures 14 and Figure 15, this system is applicable to a practical analysis of the consolidation phenomenon.

7. SUMMARY AND CONCLUSION

As the literature suggests, the magnitudes and rates of the consolidation settlement of soft clay is significant interest to both practical engineers and researchers. In this paper, as a new approach to solve this problem, the basic concept and development procedure of the hybrid-online consolidation testing system considering pore water migration was introduced.

Especially, two major points can be raised for advantages of the system. Firstly, in this simulation method, nonlinear properties of soil measured directly from the undisturbed soil can be introduced to numerical calculation. Therefore, the complicated parameter selection process is not necessary. Consequently, it is possible to reduce the errors, which could be occurred in parameter estimation and selection process. By using this point, the applicability of system was expected to extend to the consolidation problems, which was difficult in formulation of stress strain behavior like organic soil, very soft clay and environmental waste landfill soil. Secondly, since this system adopted the infinitesimal control of volumetric strain, more precious and reasonable simulation on the consolidation phenomenon can be reserved when compared with the case using the stress strain behavior obtained by multiple staged loading (MSL) test. That is, especially, complicate and strong nonlinear stress strain behavior like decrease of effective stress and delay of pore water dissipation phenomenon by cementation, softening and structure collapse near the preconsolidation pressure can be considered in the consolidation settlement analysis by introducing the these factors from undisturbed soil specimen with infinitesimal change of effective stress.

Furthermore, the simple illustrative simulation was conducted using fully reconstituted Kaolinite specimen to verify operation stability of system. As a result, the magnitudes and rate of the consolidation settlement obtained by the hybrid-online simulation was applicable to a practical analysis of the consolidation phenomenon.

Finally, the hybrid-online consolidation analysis system is an integrated system involving a device control technique and numerical analysis, and we expect that the system and technique will contribute substantially to the advancement of the geotechnical simulation methods for various applications.

(접수일자 : 2005년 9월 6일)

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