JOURNAL OF THE KOREAN SOCIETY OF AGRICULTURAL ENGINEERS, MAR. 2005, pp. 87-96

한국농공학회논문집
제47권 제2호

Estimation of Degree of Consolidation in Soft Ground Using Field Measurements and Rheology Model

현장 계측치와 유변학적 모형을 이용한 연약지반의 압밀도 추정

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Abstract

In this research, an attempt is made to derive the practical estimation of the degree of consolidation in soft clay from field measurements under embankments. For the practical estimation of pore water pressure in soft clay, the elasto-viscous rheological model was proposed, with a transform of parameters and a field geotechnical measurements in southern Korea. By using the rheological properties of soft clays and the dissipation of excess pore water pressure behaviour during step loading, a degree of consolidation or pore water pressure estimation in the future can be performed, and are shown to be generally close to the field measurements of pore water pressure. Finally, a pore water pressure behaviour in soft clay can be explained through measured data in field and the excess pore water pressure data can also be used to estimate settlement.

Keywords : Degree of consolidation, Excess pore water pressure, elasto-viscous rheological model; field measurements

I. 서 론

Soft ground has complicated soil properties according to the composition structure and the combination condition of soil by not only environment of a sedimentary process, but also external environment after sedimentation. Such complicated properties cause many problems in terms of planning, construction, and maintenance of various structures.

The analysis of the acute settlement and the degree of consolidation of soft ground is the necessary fact of a soil structure plan. The estimation of degree of consolidation is the most considerable fact as to determine the amendment confirmation of ground improvement, the con-

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solidation completion point, and the final embankment height of soft ground.

The estimation method of degree of consolidation in the field is often used after estimating the final settlement from the settlement data of field measurements. However, at the early measurement, the degree of consolidation is low and the measured data is not enough. So, the error of estimated degree of consolidation is so high that it is not easy to verify credibility and if degree of consolidation is low, the settlement and declination can be estimated larger. Therefore, in case that degree of consolidation of ground is low, to estimate degree of consolidation using the pore water pressure which measured data is sufficient at the early consolidation is more rational than to estimate degree of consolidation with settlement measurement data. Especially, since rheology was introduced, soil mechanics has actively been doing research about the rheological analyses it with the flow on external load, the deformation after idealizing behaviour of soil with elasticity, plasticity, and viscosity.[1,2,6]

This study is to induce estimation formulation based on existing degree of consolidation and rheological theory in order to estimate degree of consolidation with credibility using dissipation of excess pore water pressure after embankment completion under the soft ground improvement sites on the domestic southern coast, and to compare and analyse it with field real measurement for estimation of practicality.

II. Proposition of degree of consolidation

It is the rheological model that describe a consolidation phenomenon so mathematically properly. The rheological model which has been studied so far is suggested in order to clarify the behaviour after the secondary consolidation as creep.[7,9,10] The secondary consolidation is done after the primary consolidation,[5] but it is difficult to distinguish it strictly and it is also natural to describe all the deformation including immediate settlement and the primary consolidation settlement with rheological model. There are Kelvin model and Bingham model among representative models which the behaviour of soil structure related to effective stress has a relation with degree of consolidation, pore water pressure, and time.

Analysis of degree of consolidation of soft ground is divided and compared with the degree of consolidation calculated with settlement and pore water pressure, however it is true to contain many errors in estimation of degree of consolidation. This study had measured data of pore water pressure and induced comparatively practical and compact estimation formulation as the process of Fig. 1.

Inducement of estimation considered dissipa-

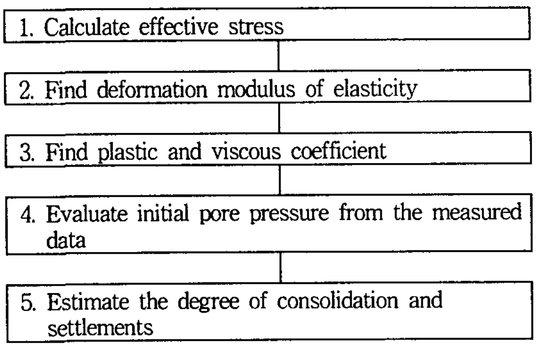

Fig. 1 Identification procedure for rheological model

tion of pore water pressure on step banking as form like settlement and introduced Kelvin model of Komamura(1974)[3] and instant compression which Rajot(1992)[8] suggested. Based on Kelvin model, the rheological model was induced like Fig. 2, which put the elastic spring model that indicated immediate settlement above and put the viscous dashpot that showed residual settlement below. And with this model, the degree of consolidation by pore water pressure was estimated.

Basically, linear elasticity spring is described as $\sigma = E \cdot \varepsilon$ and dashpot $\sigma = \eta \cdot \dot{\varepsilon}$. Here are $\sigma =$ loading pressure (kPa), $\varepsilon =$ strain, E = spring constant of model (kPa), η = dashpot constant which indicates viscosity of model and $\dot{\varepsilon}$=strain velocity (1/day). Also, as total stress incremental $\triangle\sigma$ is the sum of effective stress and pore water pressure, the change of the effective stress is same with the change of spring and the change of the pore water pressure is similar to the change of dashpot, so it is described as $u_t = \sigma_0 e^{-(E/\eta)t}$. The effective stress is needed to calculate the elastic modulus of material for a model set-up. In clay soil, there is also the early elastic deformation without relaxation time. Therefore, the spring of Kelvin model has a principle of using the elastic modulus which shows properties of material. However, excess pore water pressure on effective stress is generally an one-dimensional linearity relation, so it is proved that the application of pore water pressure is acceptable for elastic deformation modulus of material. This study took the dissipated amount of pore water pressure after step loading of step banking as appearance of stress and used it after calculating deformation modulus.

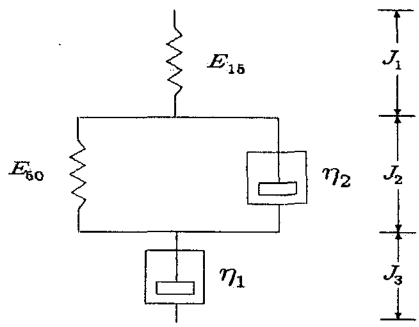

Fig. 2 Rheological model

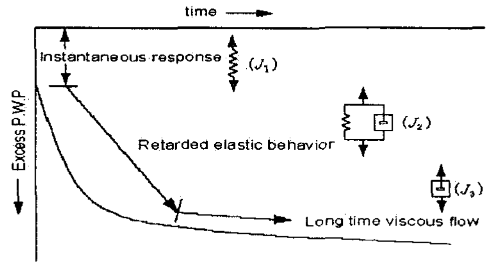

Fig. 3 Elasto-viscosity of proposed model

The decision of viscous modulus is considered so importantly in understanding rheological behaviour. Loading pressure, strain and property of time show the creep deformation of stress relaxation. Rheology is used properly to show creep and gradual deformation. In consolidation, deformation and void ratio are estimated. But, this study is to estimate the change of pore water pressure with time and calculate the degree of consolidation. The component of the estimation formulation which uses it after compounding elasticity, plasticity, and viscosity is as follows.

$$u_t = f(t) = f(u_i, \triangle\sigma', E_{15}, E_{50}, \eta_1, \eta_2, t) \quad (1)$$

Here the estimation formulation is the one which expresses elastic and viscous properties by time.

In other words, it can be divided into three parts such as the part which immediately strained and pore water pressure is dissipated (J_1), the part which applied elastic decrease and viscous effect (J_2), and the viscous part which appears as action stress goes beyond limit stress (J_3).

$$u_t = u_i(J_1 + J_2 + J_3) \cdots\cdots (2)$$

Part J_1 is assumed as a perfect elastic body which Hook's law works, and indicates the dissipation of pore water pressure by immediate strain without relaxation time. Namely, it is strain of elastic spring of viscous material and is the concept of immediate compression out of models which Rajot(1992) suggested. Part J_2 as a traditional Kelvin form can apply spring and dashpot s model with many constants.

Part J_3 is viscous strain by time. In general, as the step to happen when it passes over a viscous limit, it is difficult to divide clearly. But, the part J_3 can show the dissipation process of pore water pressure by time after it acts on dashpot body of viscous material and is assumed as the flow of viscous body which Newton's law functions. The estimation applied to early excess pore water pressure with composition of 3 parts stated above is as follows.

$$u_t = u_i(J_1 + J_2 + J_3) = u_i[(\frac{A \cdot \sigma_v'}{E_{15}}) + \exp(\frac{B \cdot E_{50} \cdot t}{\eta_2}) + (\frac{t \cdot \sigma_v'}{\eta_1})] \cdots (3)$$

Therefore, degree of consolidation U_t can be described as the following formulation.

$$U_t = \frac{u_i - u_i[(\frac{A \cdot \sigma_v'}{E_{15}}) + \exp(\frac{B \cdot E_{50} \cdot t}{\eta_2}) + (\frac{t \cdot \sigma_v'}{\eta_1})]}{u_i} \cdots\cdots (4)$$

After setting up the initial condition and boundary condition at basic differential con-solidation equation, it should be find out the solution or pore water pressure. Calibration constant A as the coefficient to calibrate initial excess pore water pressure is kind of initial condition, and is the calibration for the error of measurement and uncertainty of the ground mechanical properties. Calibration constant B as a boundary condition is the calibration constant which induced model formulation satisfies formulation and passes the point of the final excess pore pressure of step banking. Until satisfying convergence criterion in the light of analysis of numerical value, it did computed treatment so as to pass the point of initial excess pore water pressure and the point of final pore water pressure of step banking and it made the compassion possible through indicating the numerical value on a graph.

III. Materials and Methods

1. Study Sites

Field measurements and data for an experiment quoted the data conducted by three soft ground improvement methods(Menard drain method, pack drain method, prefabricated vertical drain: PVD method) at the project areas of a residential development project(Lee et. al 2002).[4]

Period of embankment construction carried out

Table 1 Geotechnical properties at various site

Site (Depth)	N value	w_n (%)	e_0	q_u (kN/m^2)	C_c	C_α	OCR	C_v (cm^2/s)	Embankment γ_t (kN/m^3)	Drain dia. (dw) (cm)	Spacing of drain (Depth of drain)
Menard drain (30 m)	2~4	45~ 70	1.27~ 1.80	21.6~ 93.2	0.460~ 0.891	0.005~ 0.025	0.49~ 1.70	1.43×10^{-3}~ 3.47×10^{-4}	18.78	5.0	1.0×1.0 m (25.5 m)
Pack drain (30 m)	2~4	40~ 70	1.14~ 1.89	11.8~ 54.0	0.500~ 0.852	0.003~ 0.021	0.37~ 1.47	1.19×10^{-3}~ 3.53×10^{-4}	19.01	12.0	1.0×1.0 m (25.5 m)
PVD method (30 m)	2~4	38~ 70	1.20~ 1.89	14.7~ 91.2	0.515~ 0.967	0.006~ 0.019	0.55~ 1.72	1.05×10^{-3}~ 3.43×10^{-4}	19.24	6.6	1.0×1.0 m (25.5 m)

for about 145 days including soft ground improvement period, period of embankment after construction end measured settlement for 200 days, areas of test site was 45 m×50 m and embankment height was constructed after adjusting to each 5.0 m. The field and laboratory experiment conducted to investigate distribution characteristic of soft ground, physical property, and geotechnical properties is as same as Table 1.

2. Estimation of Rheological Model Constant

Based on settlement and excess pore water pressure measured from Menard drain method, pack drain method, and PVD method, it found out spring constant and dashpot constant and quoted them in order to compare pore water pressure with settlement.

Measured data used the data by end of step banking to emphasize practicality and the data after that was used to compare estimation formulation. The excess pore water pressure of Menard drain method, pack drain method, and PVD method measured from middle depth of a soft layer at the point of end of step banking was 111.83 kPa, 96.14 kPa, and 114.78 kPa respectively. And, pack drain method was the least one.

1) Determination of Spring Constant

Fig. 4 shows the pore water pressure and dissipation amount produced during period of embankment construction and excess pore water pressure which cumulates increased amount, and dissipation amount.

Namely, it indicates the transferred dissipation amount of excess pore water pressure produced

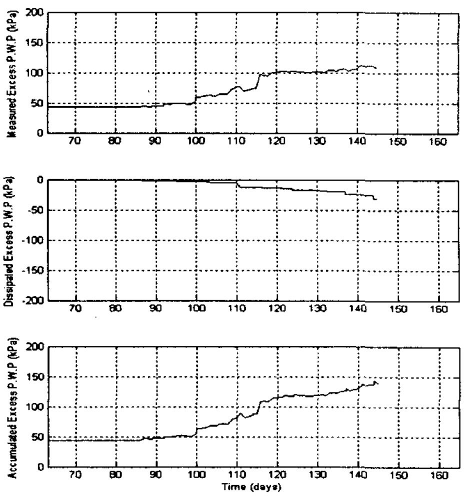

Fig. 4 Variations of accumulated excess pore water pressure by Menard drain method

period after step banking as the increased amount of excess pore water pressure produced during period of step loading. And, it was used to determine spring constant.

Fig. 5 shows the deformation modulus by Menard drain method. The excess pore water pressure on effective stress is generally an one-dimensional linearity relation, so this study took the dissipated amount of pore water pressure after step loading as appearance of

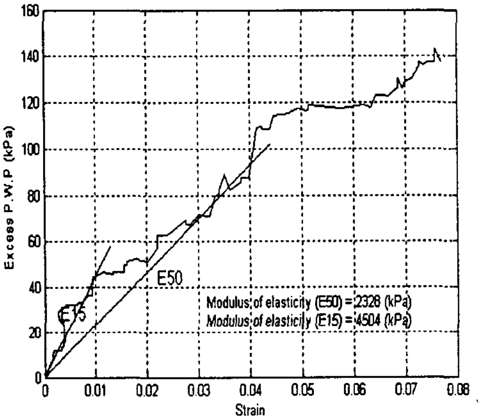

Fig. 5 Deformation modulus by Menard drain method

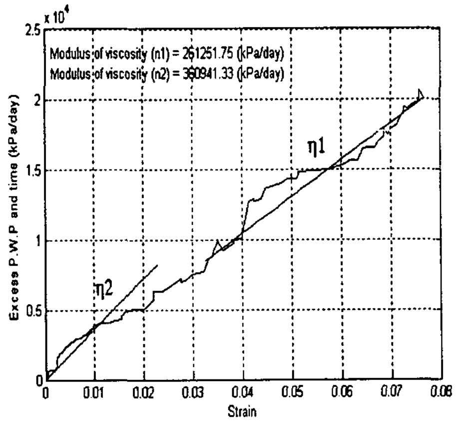

Fig. 6 Viscosity parameters by Menard drain method

Table 2 Spring parameters

Description	Methods		
	Menard	Pack	PVD
E_{15} (kPa)	4,504	5,442	5,748
E_{50} (kPa)	2,328	2,993	3,044

stress and used it after calculating deformation modulus.

When the initial strain of embankment was taken as the strain form of elasticity-plasticity-viscosity, it was considered as the form of 15~20% of total settlement. And, initial tangent modulus(E_{15}) was shown as the increased amount of pore water pressure on strain ratio of 15% of total settlement of step banking. The strain modulus of material used the concept of traditional secant modulus as it was.

Dissipation amount of pore water pressure was 30.43 kPa, 51.79 kPa, 36.30 kPa in order according to Menard, pack, and PVD method. And, pack drain method was the least out of three methods. The spring constant for each method was calculated like Table 2.

2) Determination of Dashpot Constant

Viscous modulus is so important to investigate rheological behaviour, and it indicates relaxation time in relation to loading pressure, strain, and time. Because soil is not perfect elastic body, it can be applied to Newton s law in addition to elasticity s law. In other words, it needs the application of viscous modulus of relaxation time including elastic stress-strain. Like a proposed formulation, the relation of strain rate($\dot{\varepsilon}$) and stress(σ) is viscous modulus, dashpot constant of the proposed model was shown in Table 3 and

Table 3 Dashpot parameters

Description	Methods		
	Menard	Pack	PVD
η_1 (kPa/day)	261,252	262,913	272,692
η_2 (kPa/day)	360,941	509,978	512,067

Fig. 6.

Dashpot constant is described as $\eta = \sigma / \dot{\varepsilon}$ and strain velocity $\dot{\varepsilon} = \varepsilon / t$.

Dashpot constant η_1 like viscosity model or Bingham model shows relaxation of viscous model, and constant η_2 indicates elastic strain of spring of Kelvin body with viscosity of relaxation time. Generally, the dashpot constant is decreased as the water content increases. It will be equal to the water if the water content is very large.

The dashpot constant of Menard drain method, pack drain method, and PVD method, like the relation of traditional stress−strain ratio, showed that η_2 was slightly larger than η_1.

3) Determination of initial excess pore water pressure

At first, initial excess pore water pressure (u_i) should be taken into consideration in order to estimate degree of consolidation. If step load works gradually on the saturated soft ground, the dissipation of total excess pore water pressure indicates complicate behaviour produced after composing the dissipation during banking construction and the dissipation after maximum excess pore water pressure. Therefore, like Fig. 7, based on pore water pressure with end of step banking, it found out initial pore water pressure after collecting only dissipation of pore water pressure after various steps banking.

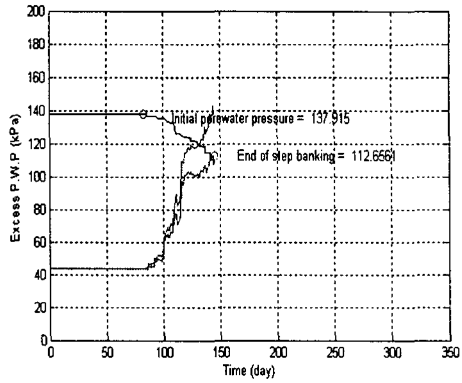

Fig. 7 Excess pore water pressure at initial by and at end of step banking

And then, we reflected the dissipated excess pore water pressure rationally from initial embankment to the end of embankment. This study assumed that analysed ground was normally consolidation state, and because dissipation rate was slow, it assumed that the dissipation phenomenon of pore water pressure or primary elastic strain included decrease of effective stress by viscous strain. The initial pore water pressure produced according to Menard, pack and PVD method was 137.9 kPa, 145.4 kPa, and 145.5 kPa respectively.

IV. Application of Proposed Formulation

1. Estimation of Excess Pore Water Pressure

Fig. 8 is to estimate pore water pressure of Menard drain method by proposed formulation. In other words, the dissipation process of pore water pressure was estimated from the data of excess pore pressure dissipated out of step banking, and we compared and analysed it using dissipation data of the pore water pressure and

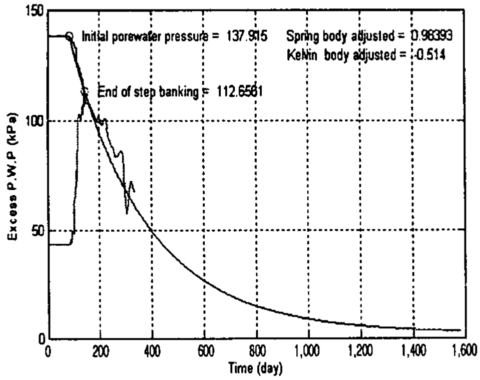

Fig. 8 Proposed excess pore water pressure Menard drain method

measured data after embankment construction. The pore water pressure by proposed formulation is dissipated faster than measured pore water pressure. This is caused because in the process of soft ground improvement, permeability coefficient decreases by smear effect and well resistance of surrounding ground through installment of prefabricated vertical drains. It is represent the measured excess pore pressure is dissipated late. At the pore water pressure of pack drain method and PVD method, proposed value is dissipated faster than measured value like Menard drain method.

The proposed formulation was adjusted to pass initial pore water pressure of end of embankment construction. Calibration constant A of the suggested formulation is the constant which calibrates the process that the initial pore water pressure produced from the proposed formulation transforms exponentially, spring constant calculated as measured value, and the error of dashpot constant. Calibration constant is 0.98 or so in Menard drain, pack drain, and PVD method, and the first term of the proposed formulation shows dissipation of initial pore water pressure well without large calibration.

Since calibration constant B is the relation of pore water pressure dissipated out of step banking and strain rate, there are more measured errors. After embankment construction, the pore water pressure by the proposed formulation should be match with first measured value, so it is the calibration constant which can pass the measured value of final pore water pressure of end of embankment construction and absorb the error. Calibration constant was −0.51, −1, and −0.64 respectively in Menard drain, pack drain, PVD method, and the pack drain method was matched well with the proposed formulation without adjustment of calibration constant. Menard drain and PVD method indicated relatively closeness when it were compared to pore water pressure of embankment.

2. Estimation of Degree of Consolidation

Fig. 9 is to compare the estimated excess pore water pressure by the proposed formulation and measured excess pore water pressure. Equality (%) becomes 0% when measured value and proposed value are matched and it indicates the difference as inclination. Menard drain method was very approachable when it was at initial measurement or excess pore water pressure was high. But, as time went by, gradually the proposed excess pore water pressure was a little small and the equality showed 4%. pack drain and PVD method was approachable at initial measurement. but, as time went by, degree of dispersion of proposed value and measured value was larger and larger.

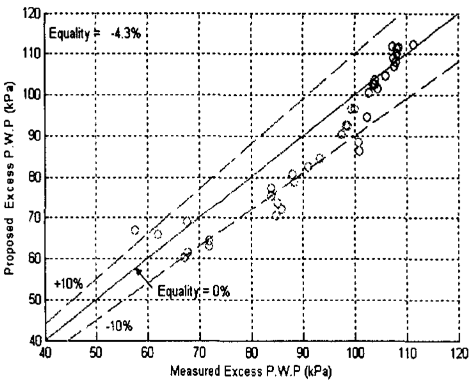

Fig. 9 Measured and proposed pore water pressure by Menard drain method

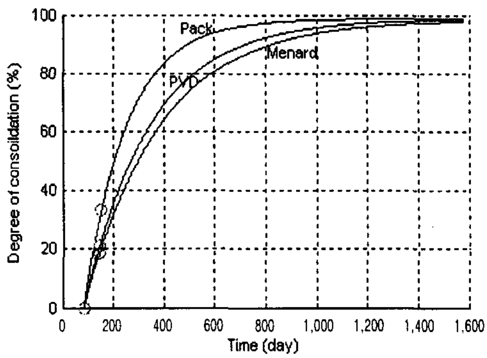

Fig. 10 Proposed degree of consolidation by each method

And, equality of pack and PVD method showed 16.7% and 19.1% respectively.

Such a reason shows that as a clay particle is rearranged by surrounding smear in the drain penetration unlike Menard drain method, the dissipation velocity of excess pore water pressure gets late and equality is not somewhat satisfactory.

Fig. 10 is to indicate the degree of consolidation of Menard drain, pack drain and PVD method estimated with excess pore water pressure. The initial excess pore water pressure induced by the proposed formulation appeared the degree of consolidation considering excess pore water pressure dissipated from embankment construction, and made it possible to confirm the degree of consolidation by passing time.

The proposed degree of consolidation by time indicated difference according to ground improvement method and the increased tendency was similar. However, Pack drain method increased a little fast and Menard and PVD method were similar. A distribution tendency was shown as the form of a parabola similar to one-dimensional degree of consolidation curve of Terzaghi. And, As period after embankment construction, the degree of consolidation increased radically, different with measured value. When degree of consolidation was 90%, it took such long time as about 500~800 days. And as time went by, it appeared nearly each other.

V. Conclusions

This study proposed the formulation which could estimate consolidation with credibility, based on existing consolidation and rheological theory, from excess pore water pressure measured on the soft ground of the southern coast in Korea. And also, it compared and analysed the excess pore water pressure measured, verifying the application. As the result of that, the conclusion is as follows.

1. The determination method of elasticity and viscosity strain constant was suggested newly and applied it to the proposed elasto-viscous rheological model with consideration of dissipated excess pore water pressure, settlement, and strain velocity.

2. Using excess pore water pressure measured

during period of step banking, it proposed the rheological model which can estimate excess pore water pressure after end of banking and evaluated equality(%) comparing with field measured value. And, the result was shown 4~19% or so.

3. The degree of consolidation estimated rheologically using dissipation of excess pore water pressure increased a little fast in pack drain method, and Menard drain method and PVD method showed a similar trend each other. As period after embankment construction, the degree of consolidation increased radically, different with the measured value.

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