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ELASTO-VISCOUS MODELLING OF TIME-DEPENDENT BEHAVIOR OF CLAY

MODELE ELASTO-VISQUEUX DE COMPORTEMENT EN FONCTION DU TEMPS DE L'ARGILE

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SYNOPSIS: It is suggested that deformation behavior of clays under extremely small strain rates in consolidation phenomena is more appropriately interpreted from the view of elasto-viscous liquids rather than visco-elastic plastic solids. A rheological equation is proposed and the method for determining necessary parameters is described based on the rheological equation as well as the results of long-term consolidation tests. The applicability of the proposed model is validated by the results of constant rate of strain consolidation tests. From the test results and numerical predictions, deflection points in the compression curves may be interpreted not by a yielding phenomenon but by a transient phenomenon of elasto-viscous liquids associated with the change in strain rate. Its steady part corresponds to normally consolidated compression curves. The location of compression curves is dependent of strain rate and independent of preconsolidation pressure.

INTRODUCTION

It is of vital importance to have a rational interpretation of compression curves of soil to arrive at a more reliable theory of consolidation. The history of interpretations of the compression curves itself may be regarded as a center of the history of consolidation study. Many earlier research workers such as Terzaghi have focussed on a single compression curve, regarding clay particles as an elastic solid, upon which current conventional analytical methods for consolidation are based.

Studies by Crawford(1964) and Bjerrum(1967), who examined the effect of secondary consolidation on the compression curves, have widened up our view of consolidation studies from a single compression curve to a family of compression curves. Most of research workers then have interpreted the family of compression curves as the result of behavior of visco-elastic plastic solids, and have constructed a model which behaves elastically in overconsolidated (OC) regions and plastically in normally consolidated (NC) regions.

Information obtained from laboratory tests, however, seems to deny purely elastic behavior in the OC regions. For instance, phenomena of effective stress relaxation shown by Holzer et al.(1973), and of secondary consolidation in the OC regions observed by Ikegami et al.(1989), clearly belong to behavior of a group of elasto-viscous liquids. The results of constant rate of strain compression tests carried by Leroull(1985) showed that there exists no fundamental differences in the behavior of clay between NC and OC regions. The information leads to suggest that clay behaves much more like as a liquid than as a solid under extremely small strain rates, often appeared in consolidation phenomena. This study examines two separate consolidation test results, long term and constant rate of strain tests, from the viewpoint of elasto-viscous liquid.

RHEOLOGICAL EQUATIONS

Experimental findings obtained so far on compression behavior of reconstituted clays may be summarized as follows;(a) Behavior of clays cannot be distinguished between NC and OC regions in rheological terms.(b) A part of compression deformations is recoverable.(c) Compression deformations are time-dependent and do not converge.(d) Clays possess the characteristics of retarded elasticity.(e) Clays exhibit effective stress relaxation. Putting these findings together, a rheological model will emerge for soft clays, as is depicted in Fig.1(a), which is a liquid of elasto-viscosity exhibiting retarded elasticity. Detailed discussions on how we arrive at the elasto-viscous liquid will be published in elsewhere.

Retarded elasticity is ignored in this study, leading to a simpler rheological model shown in Fig.1(b). This is partly because the authors have not identified what viscosity contributes retarded elasticity, and also because little effect of retarded elasticity is supposed on the process of consolidation, since a rate of effective stresses in the field is considered much smaller than those in the laboratory.

Letting e void ratio and σ' effective stress, the rheological equation for the model shown in Fig.1(b) is written in a form of

$$\frac{de}{dt} = -\left(m_v \frac{d\sigma'}{dt} + \frac{1}{\eta}\sigma'\right) \qquad (1)$$

where m_v is the coefficient of volume change, and η the coefficient of viscosity, which are respectively defined by

$$m_v=-\frac{de}{d\sigma'} \tag{2}$$

$$\sigma'=-\eta\frac{de}{dt} \tag{3}$$

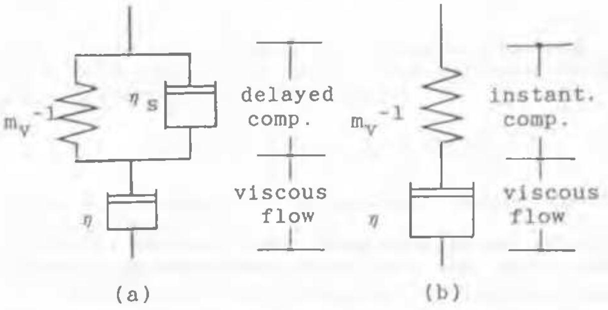

Fig.1. Elasto-viscous liquid models

LONG-TERM CONSOLIDATION TESTS

A series of long-term consolidation (LT) tests was carried out to determine the value of η. The clay used was Hiroshima clay, of which liquid and plastic limits are 116.5 and 45.4 %, and specific gravity 2.623. The clay was reconstituted at a water content of about 240% and sieved through a 420μm mesh. The clay slurry thus obtained was then consolidated under a pressure of 49kPa. Using oedometer test apparatus of 60mm in diameter, 20mm in thickness, two sets of LT tests were performed under five different consolidation pressures of 78.4, 156.8, 313.6, 627.2 and 1254.4 kPa. A step loading sequence with a load increment ratio of unity was adopted during preliminary consolidation. The consolidation pressures were increased about 30mins after the application of the previous pressure. By that time the primary consolidation due to the previous pressures was supposed to terminate. A particular reason for this was that the clay samples were to be tested, while the clay samples still remained the state of "young" and exhibit clear secondary consolidation phenomena.

Fig.2 presents all the test data of void ratio (e) plotted against elapse time (t) in a semi-log scale. Linear relationships between e and log t appear in the portions of secondary consolidation, from which the coefficients of secondary consolidation (C_α) were determined. The data of void ratio (e) under the final consolidation pressures are replotted against creep rate(e=de/dt) in a semi-log scale shown in Fig.3, where a linear relationship between e - log e can be seen in the secondary compression portions. It was found that although some scatters were noticed in the small effective stress level, the value of C_α may be taken as a constant value of 0.016 over the test pressure range. Based on the results of Fig.3, a family of equi-creep-rate lines of secondary consolidation is depicted in Fig.4.

Together with well established relationships, the following three approximations are adopted for the above test results.
Approximation - (1) As to Fig.2, the curves of secondary consolidation are a series of straight lines parallel to each other, having the gradient of C_α. The value of C_α is constant regardless of stress level;

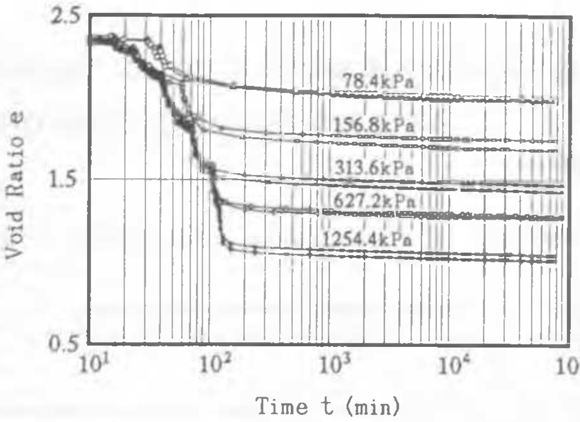

Fig.2. Consolidation curves under various pressures in long-term consolidation tests

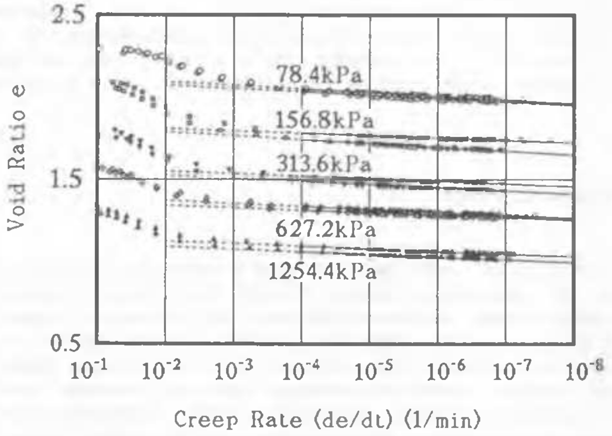

Fig.3. Decrease in creep rate in long-term consolidation tests

$$\frac{de}{dT}=-C_\alpha \tag{4}$$

$$\frac{de}{dt}=-\frac{0.434}{t}C_\alpha \tag{5}$$

where T=log t .

Approximation - (2) As to Fig.4, the equi-creep-rate lines of secondary consolidation are a group of parallel straight lines, having the gradient of C_β. That is to say,

$$\left(\frac{de}{d\Sigma'}\right)_{\dot{e}=const}=-C_\beta \quad , \tag{6}$$

$$\left(\frac{de}{d\sigma'}\right)_{\dot{e}=const}=-\frac{0.434}{\sigma'}C_\beta \quad . \tag{7}$$

in which $\Sigma'=\log\sigma'$

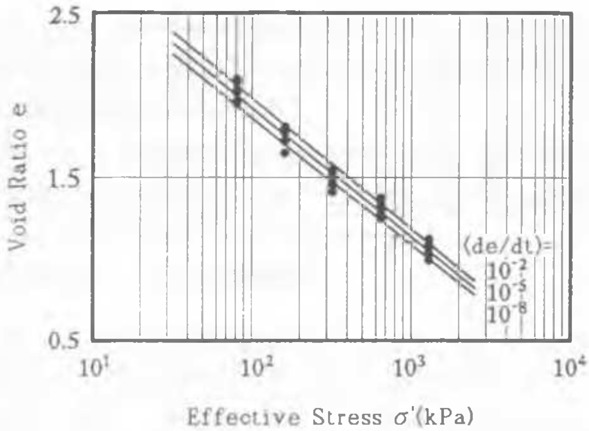

Fig.4. Equi-creep-rate lines obtained from long-term consolidation tests

Approximation - (3) Rebound (or instantaneous compression) curves are a group of parallel straight lines with a gradient of C_γ in e - logσ' curves.

$$\frac{de}{d\Sigma'} = -C_\gamma \tag{8}$$

$$\frac{de}{d\sigma'} = -\frac{0.434}{\sigma'}C_\gamma = -m_v(\sigma') \tag{9}$$

According to the approximations (1) and (2), the relationship of logη-e-logσ' forms a plane as is illustrated in Fig.5. Putting H=logη and taking the total differential of H with respect to H-e-Σ' space, we have

$$dH = \frac{\partial H}{\partial e}de + \frac{\partial H}{\partial \Sigma'}d\Sigma' \tag{10}$$

Considering that the relationship of logη-e-logσ' is a plane, Eq.(10) is rewritten as

$$\Delta H = -(C_{\eta e}\Delta e + C_{\eta\sigma'}\Delta\Sigma') \quad , \tag{11}$$

in which

$$C_{\eta e} = -\frac{\partial H}{\partial e} = \frac{1}{C_\alpha} \quad , \tag{12}$$

$$C_{\eta\sigma'} = -\frac{\partial H}{\partial \Sigma'} = \frac{C_\beta}{C_\alpha} - 1 \quad . \tag{13}$$

By obtaining the value of η from Eq.(3) for any arbitrary point on the plane of e-σ', the value of η can be determined over the whole plane. Note that $\Delta H=\log(\eta+\Delta\eta)/\eta_0$, $\Delta\Sigma'=\log(\sigma'+\Delta\sigma')/\sigma'_0$.

Knowing the value of C_α, C_β and C_γ, the value of m_v can be determined from Eq.(9), and the η value from Eq.(11), respectively.

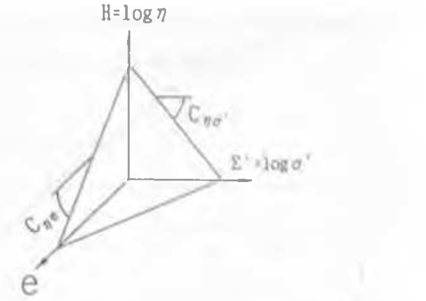

Fig.5. Relation of log η - e - log σ' under one-dimensional consolidation

CONSTANT RATE OF STRAIN CONSOLIDATION TESTS

Constant rate of strain consolidation (CRS) tests were carried out on Hiroshima clay samples having four different OCRs. The clay samples were preconsolidated under pressures of 49.0,156.8,313.6 and 627.2 kPa, and allowed to swell back to 9.8 kPa for 24 hours. The CRS tests were then commenced. Fig.6 compares the experimental data and the computational results by Eq.(1). The soil parameters used in the computations were C_α=0.016 obtained from the LT tests, and C_β=1.0 , C_γ=0.1 both determined from the gradients of the steady and the initial portions in the observed constant rate of strain compression curves. Computational curves agree well with the experimental observations. It is also understood from the computational results that the steady portions of the constant rate of strain compression curves coincide with equi-creep-rate lines.

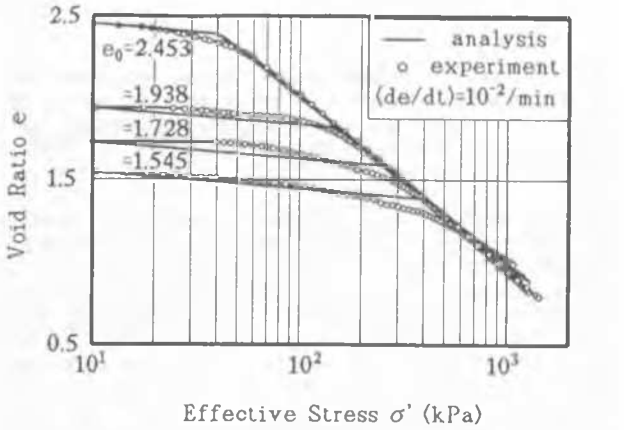

Fig.6. Constant rate of strain compression curves for various OCRs

Fig.7 is a comparison of compression curves between the LT and CRS tests in an attempt to verify the analytical conclusion. The strain rate of 0.01 $\min^{-1}$ was used in the CRS tests, which corresponds to the region where the samples were undergoing the primary consolidation in the LT tests, as is seen in Fig. 3. The void ratios were therefore evaluated by extrapolating the creep rate of the secondary compression stage. The overall agreement is seen in Fig.7, although some discrepancies are noticed in the higher stress levels.

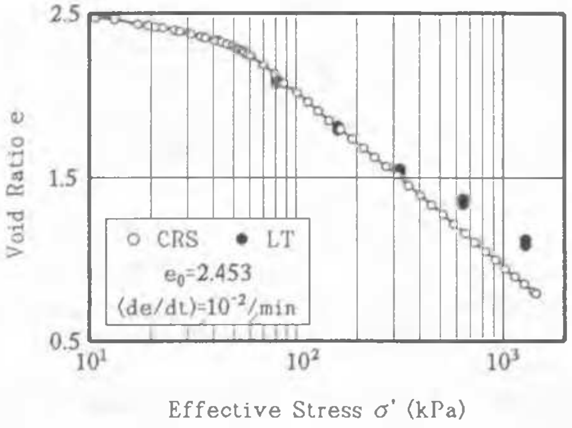

Fig.7. Comparison between constant rate of strain compression curves and equi-creep-rate lines

The fact that compression curves coincide with equi-creep-rate lines is in conformity with the observations made by Leroueil(1985) and by Imai(1989).

For the determination of the soil parameters of the elasto-viscous liquid, stable and reliable CRS tests would be suitable rather than conducting LT tests. Only two CRS tests with different strain rates are required. C_γ and C_β can be determined from the initial and steady portions of the compression curves respectively. C_α also can be calculated by obtaining the difference in void ratios between two compression curves with strain rates of $\dot{e}_1$ and $\dot{e}_2$ at a given stress. Namely

$$\Delta e = -C_\alpha \log \frac{\dot{e}_2}{\dot{e}_1} \qquad (14)$$

For CRS tests, the term de/dt in the left-hand side of Eq.(1) remains constant, which in turn is shared by the first term $(de/dt)_E$ (instantaneous compression) and the second term $(de/dt)_V$ (flow compression)in the right-hand side of Eq.(1).

The top half of Fig.8 presents an analytical prediction of the change in relative magnitudes of $(de/dt)_E$ and $(de/dt)_V$ with logσ' during the process of CRS tests. Corresponding e - logσ' relationships are also plotted in the bottom half of Fig.8. The instantaneous compression dominates the behavior and the flow compression contributes little, when the effective stress are smaller than the stress at the deflection point appeared in the calculated compression curves in Fig.6. The behavior becomes steady after experiencing a rapid transition in a narrow range immediately before the deflection point. The former is termed as OC region and the latter as NC. The stresses at the deflection point are, however, not directly related to preconsolidation pressure but depend upon current void ratio and strain rate. It is considered that the preconsolidation pressure has played a role of increasing viscosity by decreasing the void ratio, that is to say, the role of first term in the right-hand side of Eq.(10). From this point of view, it can be interpreted that the deflection of compression curves is not a yielding phenomenon but a transient phenomenon that a family of elasto-viscous liquid is experiencing the change in strain rate from one rate to another.

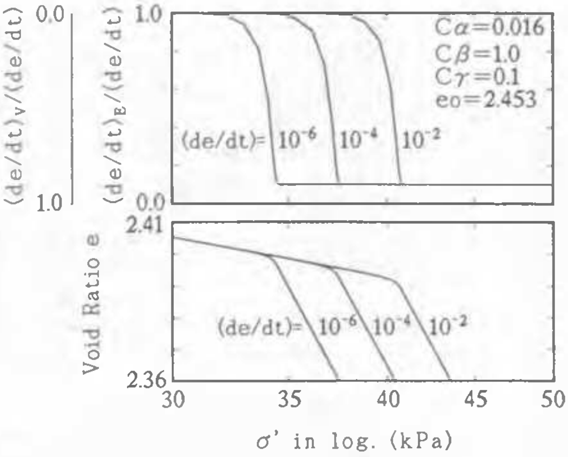

Fig.8. Transient behavior of elasto-viscous liquid in constant rate of strain compression tests

CONCLUSIONS

The following conclusions were drawn from this study.

1) From the viewpoint that clay is a elasto-viscous liquid,it is considered that overconsolidated region is a region where instantaneous compression is dominant, whereas normally consolidated region is a region where flow compression plays a dominant role.
2) The deflection appeared in the constant rate of strain compression curves is interpreted as a transient phenomenon of elasto-viscous liquids associated with the change in strain rate.
3) The location of constant rate of strain compression curves on the plane of e-logσ' is strong dependent of strain rate and independent of preconsolidation pressure.
4) Good agreement between analytical and experimental results for constant rate of strain tests supports the validity of the proposed model of an elasto-viscous liquid.
5) Parameters C_α, C_β and C_γ are considered constant on the plane of e-logσ'.

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