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Shearing Behaviors of the Soft Marine Clay in Undrained and Drained Conditions

연약해성점토의 비배수 및 배수 전단 거동

Lee, Young-Huy[*1] 이 영 휘
Kim, Yong-Jun[*2] 김 용 준
Jung, Kang-Bok[*3] 정 강 복

요 지

한반도 남해안의 광양만에서 채취한 연약 해성점토의 물리적 및 역학적 특성을 조사하기 위한 일련의 실내시험을 수행하였다. 물리적 성질 및 압밀시험 결과의 분석에 따르면, 시험에 사용된 시료는 정규압밀점토로 나타났다. 압밀비배수 삼축시험 결과로부터 새로운 간극수압계수(C)를 제안하였고, 이 계수는 유효응력경로를 예측하기 위한 방정식에 적용되었다. 또한, 비배수조건에서 전단변형률은 오로지 응력비만의 함수라는 사실이 실험결과로부터 밝혀졌다. 따라서 비배수 조건에서의 전단변형률 계산식이 제안되었으며, 이들 관계식을 이용하여 비배수(CIU) 및 배수조건(CID)에서의 점토의 거동을 예측하기 위한 새로운 구성방정식이 제안되었다. 이 구성방정식은 Roscoe와 Poorooshasb이 제안한 증분응력-변형률 이론을 기초로 하였으며, 제안된 구성방정식을 적용하여 예측한 배수전단특성은 실측된 결과에 매우 근접하는 경향을 나타내었다.

Abstract

A series of laboratory tests have been carried out to investigate the physical and mechanical characteristics of the soft marine clay obtained from the Gwangyang bay located at the southern area of the Korean peninsula. The clay is in the normally consolidated state of stress. The new pore pressure coefficient, C, is proposed from the results of the conventional triaxial(CIU) tests, and it is applied to predict the equation of the effective stress paths. The undrained shear strain can be calculated by the proposed equation formulated from the fact that the strain is the only function of the stress ratio. These two equations, i.e. the equation of the undrained stress path and undrained shear strain, are then applied to the development of a new constitutive model. The proposed model, of which main skeleton is based on the concepts of the incremental stress-strain theory by Roscoe and Poorooshasb, is used to predict the drained and undrained behaviors of the soft clay. The predicted values by the proposed model are in good agreement with the observed strains.

Keywords : Constitutive model, Incremental stress-strain theory, Pore pressure coefficient, Stress path, Soft marine clay, Triaxial tests(CIU, CID)

1. Intorduction

The marine clays, in general, show various aspects in the engineering characteristics according to their different modes of deposition. Some engineering indices of clay such as the grain size distribution, the consistency limits,

*1 Member, Professor, Dept. of Civil Engrg., Yeungnam Univ.
*2 Member, Post-Doctoral program, Dept. of Civil Engrg., Yeungnam Univ.
*3 Doctoral Student, Dept. of Civil Engrg., Yeungnam Univ.

the natural water contents and the stress history are major influencing factors to the undrained shear behaviors. A series of the laboratory tests have been performed in this study to investigate the physical and mechanical characteristics of the soft clay sampled at the sea of Gwangyang bay of southern part of Korean peninsula. The stress-strain-porewater pressure characteristics are analyzed using the results of the conventional CIU tests. Equations to predict the undrained stress path and the relationship between deviator stress and undrained shear strain are also proposed here based on certain trends observed in the test results. Based on the observations appeared from the results of CIU tests, the new incremental stress-strain model is derived to predict the shear strain and volumetric strain during the drained triaxial (CID) tests.

2. Sampling and Testing Procedures

The clayey samples were taken at the Gwangyang Bay and the detailed location of sampling site can be found in Lee et al.(1999). The quartenary clay sediments of alluvium are overlain by 6 meter thick sand layer from the sea bed. The test samples were obtained by the thin-wall tube, diameter of 76 mm, at the depth between 6 m ~ 32 m. The silty clay samples, colored in dark gray, have some inclusions of sea shells, fine particles of mica and thin layer of silty seam. The triaxial specimens were 36 mm in diameter and 77 mm in height. The applied preshear consolidation pressures are 200 kPa, 300 kPa and 400 kPa for both CIU and CID tests. Samples were saturated by applying the back pressure of 200 kPa to get the B-value greater than 0.97. The sample was sheared in undrained condition with the strain rate of 0.1 %/min and 0.008 %/min in drained condition, respectively.

3. Index Properties and Consolidation Characteristics

The natural water content of the clay is 38.3 % - 54.5 %, the liquid limit is 40.4 % - 65.2 %, the plasticity index is 19.6 % - 39.0 % and the liquidity index is ranged from 0.71 to 0.98 as shown in Fig. 1 and the grain size distributions taken from different depths reveal % passing #200 sieve of 51 % - 90 %. The clay is classified as CL or CH.

The results of oedometer tests presented in Fig. 2 show that the OCR is 1.60 at depth of 8 m and it decreases to 1.01 at depth of 25m(preconsolidation pressure: 1.1 kg/cm^2 - 2.1 kg/cm^2) and the compression index(Cc) is 0.5~0.6.

4. Definition of Stress and Strain Parameters

The stress parameters p and q are usually defined by

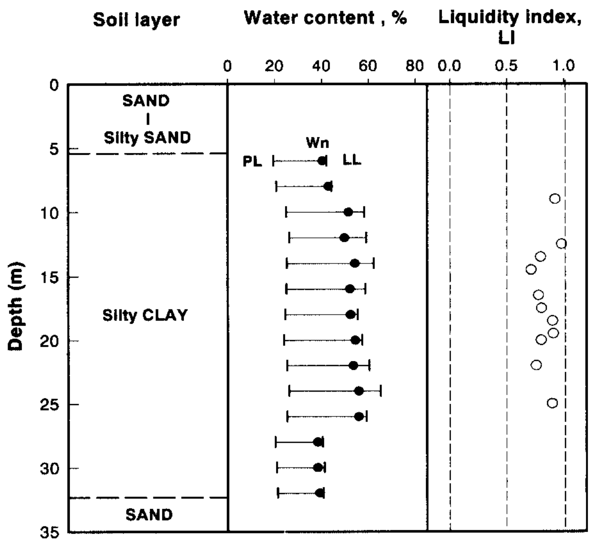


Fig. 1. Physical properties of clay with depth

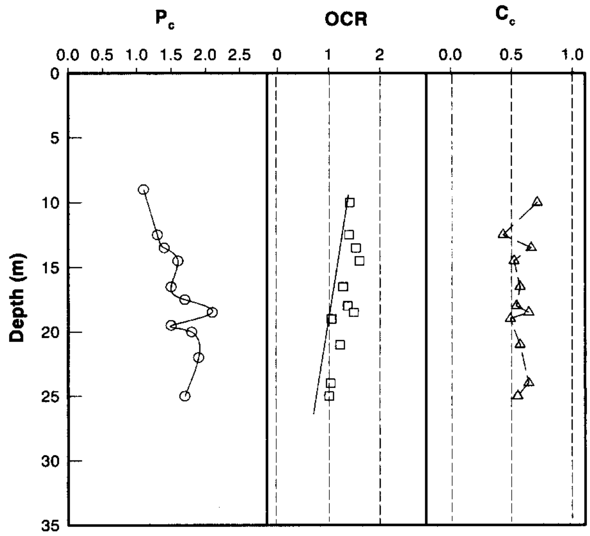


Fig. 2. Consolidation characteristics of the clay

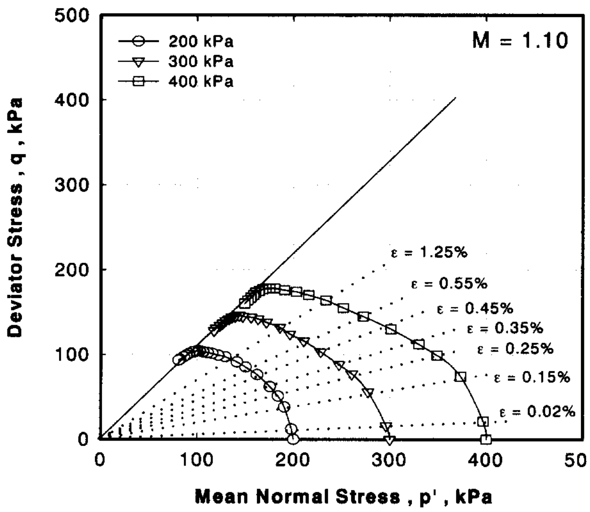


Fig. 3. Effective stress paths(from CIU test result)

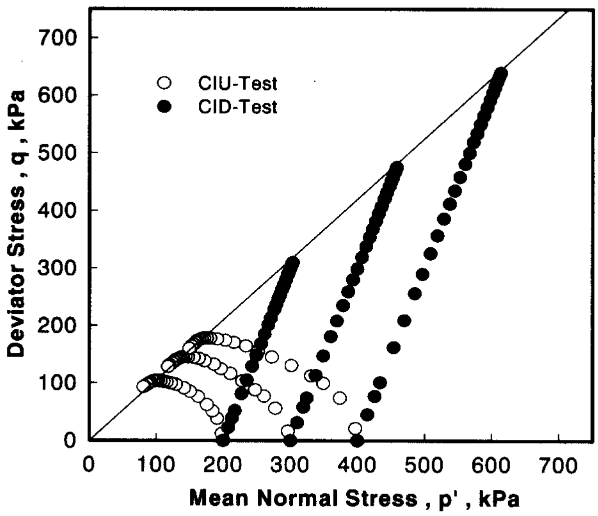


Fig. 4. Comparison of the effective stress paths(from CIU and CID test results)

$$p = \frac{\sigma_1{}' + 2\sigma_3}{3}$$
$$q = \sigma_1{}' - \sigma_3{}' \tag{1}$$

where $\sigma_1{}'$ and $\sigma_3{}'$ are the principal effective compressive stresses, and $\sigma_2{}' = \sigma_3{}'$ under the triaxial stress system. Similarly the incremental strain parameters dv and $d\varepsilon$ are given by

$$dv = d\varepsilon_1 + 2d\varepsilon_3$$
$$d\varepsilon = \frac{2}{3}(d\varepsilon_1 - d\varepsilon_3) \tag{2}$$

where $d\varepsilon_1$ and $d\varepsilon_3$ are the principal incremental compressive strains and $d\varepsilon_2$ is equal to $d\varepsilon_3$. The stress ratio, q/p, is denoted by η.

5. Triaxial Testing Results

5.1 Effective Stress Paths(from CIU and CID Tests)

Fig. 3 shows the effective stress paths followed by the specimens in the (q, p′) plot. The dashed lines superimposed in this figure correspond to constant shear strain contours. The effective stress paths are found to be virtually similar and it is possible to normalize them with preshear consolidation pressure(p_o) in the (q/p_o, p'/p_o) plot. It is also noted in Fig. 3 that the constant shear strain contours are linear and pass through the origin. In Fig. 4, the effective stress paths in both CIU test and CID test are compared. The terminal points of the stress in drained and undrained tests fall on the critical state line(CSL) which shows the M-value of 1.10.

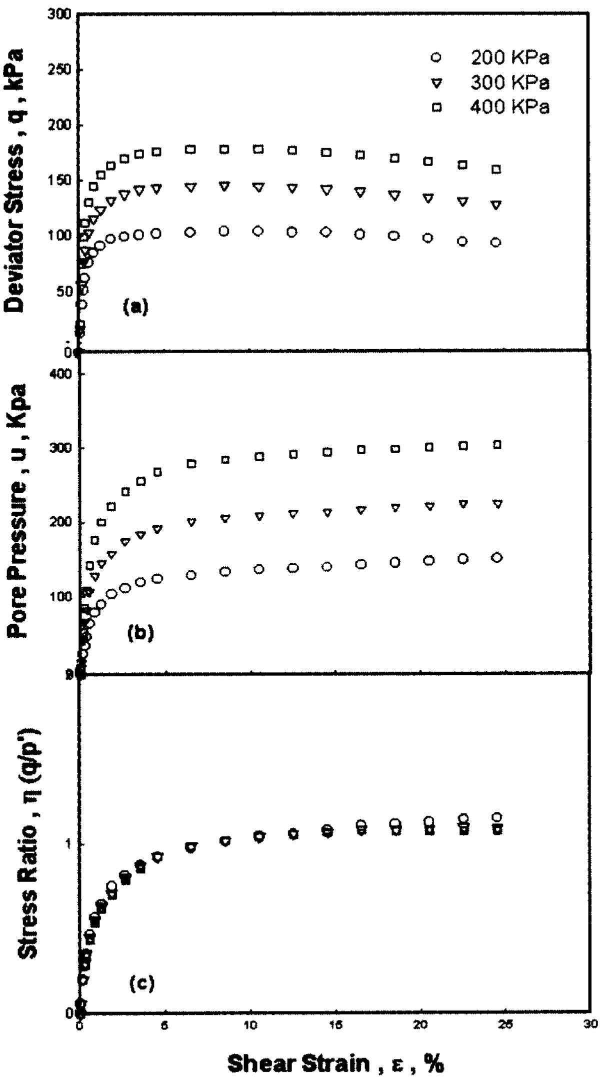
5.2 Deviator Stress - Stress Ratio - Porewater Pressure Relationship(from CIU Test)

Figs. 5(a), (b) show the deviator stress - pore pressure - shear strain relationships. In these figures, the deviator stress(q) and pore pressure were found to be same at any particular strain when it is normalized with p_o. Such a normalized behavior was previously reported for the Boston Blue clay(Ladd, 1964) and the Bangkok clay (Balasubramaniam & Chauhdry, 1978).

The relationships between stress ratio($\eta = q/p'$) and shear strain(ε) are also presented in Fig. 5(c), in which the stress ratio(η) - shear strain(ε) relationships are found to be independent of p_o.

5.3 Porewater Pressure Coefficient, C

The pore pressures(u) measured in triaxial tests are plotted against the stress ratio(η) in Fig. 6, where the (u - η) relationships are linear passing through origin for any particular value p_0. If the pore pressure is normalized with p_o, then the (u/p_o) - η relationship is appeared to



(a) Deviator stress vs shear strain (b) Stress ratio vs shear strain
(c) Pore pressure vs shear strain
Fig. 5. Stress-strain-pore pressure relationship

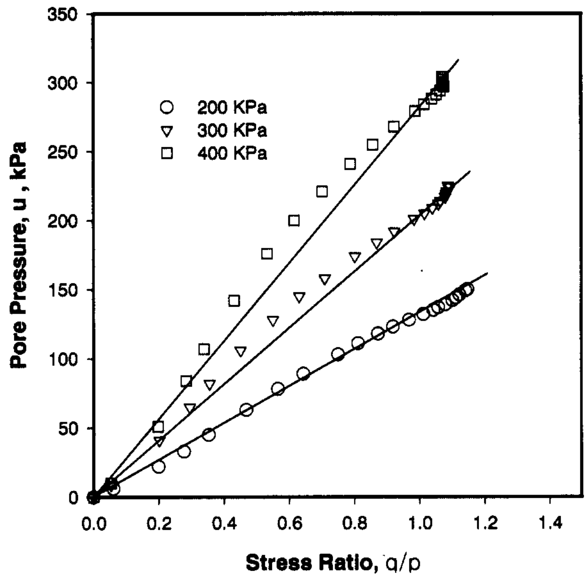


Fig. 6. Relationships between stress ratio and pore pressure

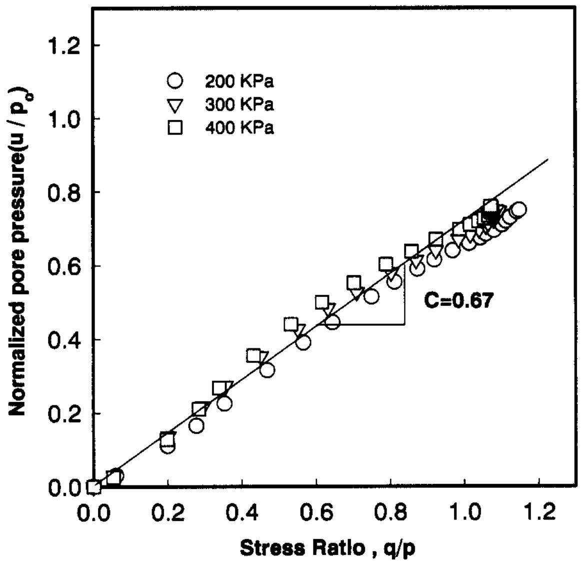


Fig. 7. Normalized pore pressure(u/p_0) vs stress ratio relationship

be a unique straight line irrespective of p_0 as shown in Fig. 7. The slope of this straight line passing through the origin is defined as the pore pressure coefficient, C, which can easily be applied to predict the equation of undrained stress path, and this will be discussed in the subsequent section.

6. Prediction of Effective Stress Path and Shear Strains(from CIU Test)

6.1 Equation of Undrained Stress Path

The slope of (u/p_0) - η relationship in Fig. 7, defined as the pore pressure coefficient, C, can be used to formulate the equation of effective stress path in triaxial stress condition as expressed in Eq. (3) and Eq. (4) in an incremental form as

$$\frac{p}{p_o} = \frac{3(1-C\eta)}{3-\eta} \qquad (3)$$

$$dp = \frac{3p_o(1-3C)d\eta}{(3-\eta)^2} \qquad (4)$$

Figure 8 compares the effective stress path which is calculated by Eq. (4) with the one measured from the test. Here, the applied consolidation pressure(p_o) is 200

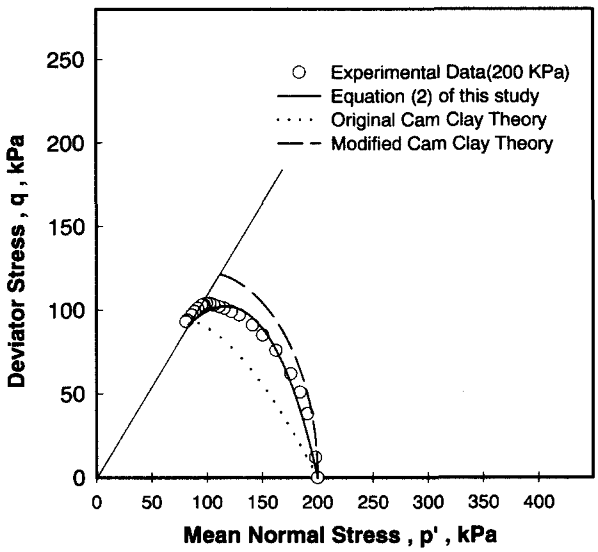


Fig. 8. Prediction of undrained stress paths

kPa and the C-value is 0.67. The results calculated from the original and modified Cam-clay theories are again superimposed in this figure with the parameter values of M=1.10, λ=0.274 and κ=0.036. It is noted in this figure that Eq. (4) gives better agreement to the measured effective stress paths than the Cam-clay theories.

6.2 Prediction of Deviator Stress - Shear Strain Relationship(from CIU Test)

Calculation of the deviator stress - shear strain relationship in CIU tests can be made from the experimental results that the shear strain(ε) is the only function of the stress ratio(η) irrespective of preshear consolidation pressure(p_o) as appeared in Fig. 5(c). The transformed hyperbolic plot of ($\varepsilon/\eta - \eta$) in Fig. 9, which gives the straight line with the intercept, 'a' and the slope, 'b' can be expressed in the incremental form:

$$d\varepsilon = \frac{a\,d\eta}{(1 - b\eta)^2} \tag{5}$$

The shear strains calculated by Eq. (5), when parameter values, a=0.007 and b=0.880 are used, are also compared with the measured values in Fig. 10. Again, the shear strains calculated from the Cam-clay theories are superimposed in this figure. The measured strains are in good agreement with Eq. (5), whereas the original Cam-clay theory overestimates the strain and the modified Cam-clay theory gives underestimation.

7. Prediction of Volumetric Strain and Shear Strain(from CID Test)

7.1 The incremental stress-strain theory

An incremental strain-strain theory for normally consolidated clay was originally proposed by Roscoe & Poorooshasb(1963), and it can be expressed by Eq. (6).

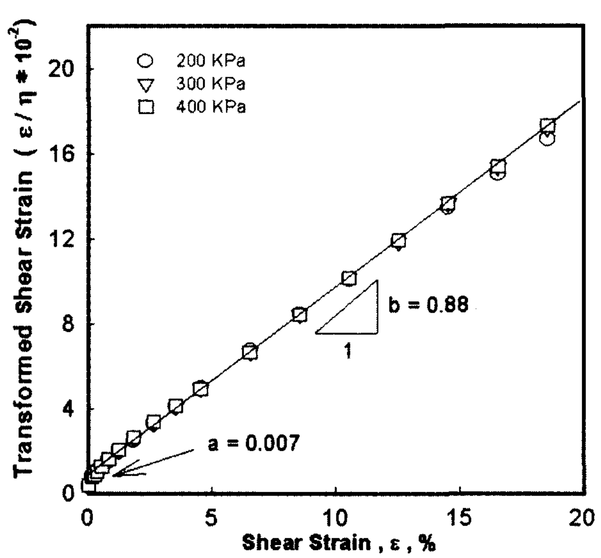


Fig. 9. Transformed shear strain vs shear strain relationship

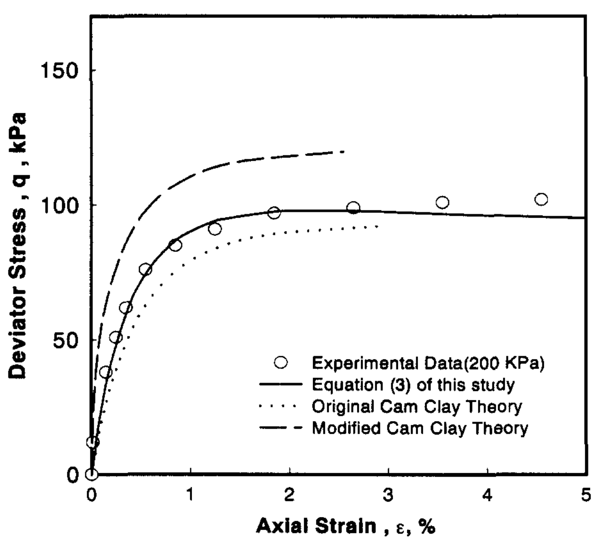


Fig. 10. Prediction of deviator stress-axial strain relationship

$$d\varepsilon_1 = \left(\frac{d\varepsilon_1}{d\eta}\right)_v d\eta + \left(\frac{d\varepsilon_1}{dv}\right)_\eta dv \qquad (6)$$

where $(d\varepsilon_1/d\eta)_v$ corresponds to the variation of $d\varepsilon_1$ with $d\eta$ in an undrained test and $(d\varepsilon_1/dv)_\eta$ represents the variation of $d\varepsilon_1$ with dv in an anisotropic consolidation stress path. The dv and $d\varepsilon_1$ are the incremental volumetric strain and axial strain respectively. Eq. (6) can be presented in a slightly different form as

$$(d\varepsilon)_{drained} = (d\varepsilon)_{undrained} + \left(\frac{d\varepsilon}{dv}\right)_\eta dv \qquad (7)$$

7.2 Incremental Volumetric Strain along the Anisotropic Consolidation Stress Path

The basic concept of the incremental stress-strain theory represented by Eq. (7) is maintained to derive the constitutive law for the normally consolidated clay. The incremental strain components along the drained path, 'a' to 'c' in Fig. 11 are equivalent to those of the undrained path, 'a' to 'b' followed by the constant stress ratio path, 'b' to 'c', within the domain of the state boundary surface (Roscoe surface). In order to implement the theory, it is therefore necessary to calculate the shear strain along the path 'a' to 'b'(volumetric strain is zero), the shear and volumetric strains along the path, 'b' to 'c'.

The magnitude of the volumetric strain increment followed by an anisotropic consolidation stress path can be determined by

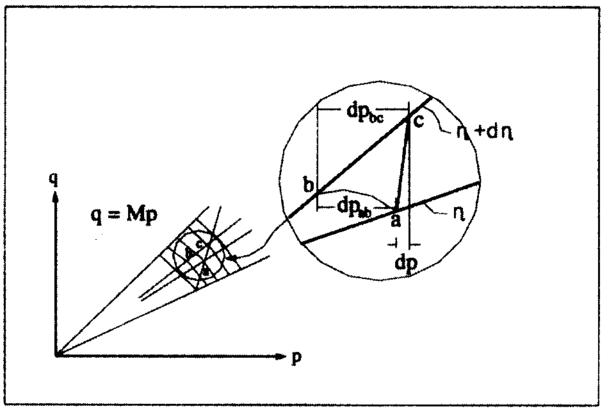


Fig. 11. Components of general stress increments

$$dv = \frac{\lambda\, dp_{bc}}{p(1+e)} \qquad (8)$$

where, 'p' and 'e' are the mean normal stress and the void ratio at point 'a' in Fig. 11 respectively, and the slope of (e -ln p) plot represented by λ is a constant for any stress ratio. The stress increment along an anisotropic consolidation stress path, 'dp_{bc}', can be estimated from the relationship in Fig.11 as

$$dp_{bc} = dp - dp_{ab} \qquad (9)$$

The magnitude of the stress decrement along the undrained stress path, dp_{ab} is equivalent to 'dp' given by Eq. (4). By substituting Eq. (4) into Eq. (9), dp_{bc} can be expressed as

$$dp_{bc} = dp - \frac{3p_{oe}(1-3C)\,d\eta}{(3-\eta)^2} \qquad (10)$$

where, p_{oe} is the equivalent preshear consolidation stress at a given value of 'p' and 'η', and this can be simply calculated from the normalization characteristics of the undrained stress path represented by Eq. (3). The volumetric strain increment, $(dv)_{bc}$ can be obtained by substituting Eq. (10) into Eq. (8).

$$(dv)_{bc} = \frac{\lambda\, dp}{p(1+e)} - \frac{3\lambda p_{oe}(1-3C)\,d\eta}{p(1+e)(3-\eta)^2} \qquad (11)$$

The plastic component of volumetric strain, $(dv)^p{}_{bc}$ is then calculated by Eq.(12) as

$$(dv)^p_{bc} = \frac{(\lambda-\kappa)\,dp}{p(1+e)} - \frac{3\lambda p_{oe}(1-3C)\,d\eta}{p(1+e)(3-\eta)^2} \qquad (12)$$

where, κ is the slope of swelling line in the (e-ln p) plot, which is also constant for any stress ratio.

7.3 Incremental Shear Strain along the Anisotropic Consolidation Stress Path

As was derived in the modified theory by Roscoe & Bunland (1968), the elastic shear strain is assumed zero and the plastic strain increment ratio is defined by

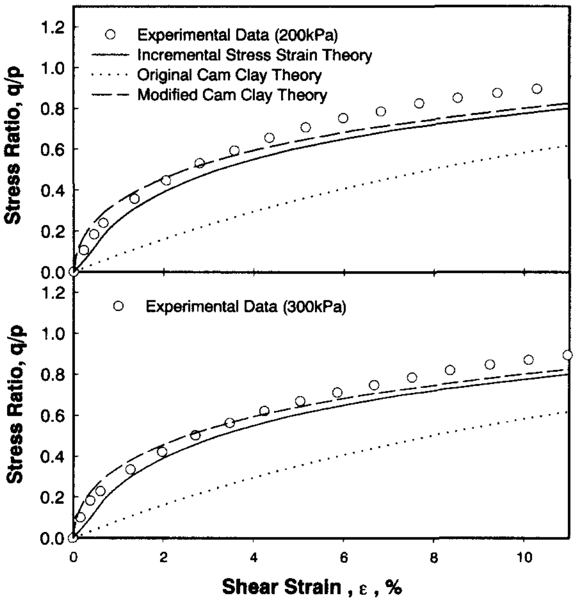


Fig. 12. Comparison of the shear strains between the measured and predicted values

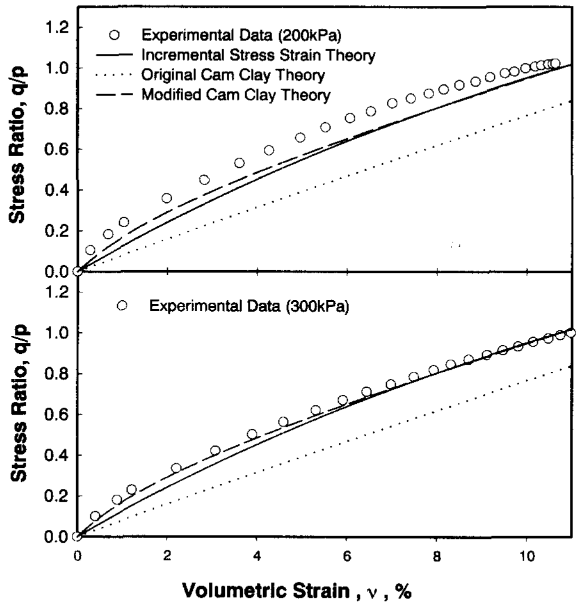


Fig. 13. Comparison of the volumetric strains between the measured and predicted values

$$\frac{d\varepsilon^p}{dv^p} = \frac{2\eta}{M^2 - \eta^2} \tag{13}$$

Then the shear strain increment along the anisotropic consolidation stress path is obtained by substituting Eq. (12) into Eq. (13).

$$d\varepsilon = d\varepsilon^p$$

$$= \frac{2\eta}{M^2 - \eta^2}\left\{\frac{(\lambda - \kappa)\,dp}{p(1+e)} - \frac{3\lambda p_{oe}(1-3C)\,d\eta}{p(1+e)(3-\eta)^2}\right\} \tag{14}$$

7.4 Verification of the model

In an undrained condition, the equation of undrained stress path is defined by Eqs. (3) and Eq. (4), the incremental shear strain can be predicted by Eq. (5). In a drained condition, the incremental volumetric strain for any stress ratio can be calculated by Eq. (11) and the shear strain increment is obtained by summation of Eq. (5) and Eq. (14).

The calculated volumetric and shear strains using the proposed model are presented in Figs. 12 and 13 respectively. The observed strains in a series of drained tests are compared with the predicted strains in the same figures. The proposed incremental stress-strain theory is found to predict very closely the measured strains, whereas the original Cam-clay model gives the extremely larger values than the measured one.

8. Conclusion

Based on analyses of the test results for the soft marine clay in Korea, the following conclusions are drawn.

(1) The pore pressure coefficient, C, is proposed from the straight line relationship in the (u/p_o)- η plot obtained from triaxial(CIU) tests. The C-value is defined by the slope of straight line passing through the origin in the (u/p_o)- η plot.

(2) The equation of the effective stress path is also proposed by incorporating the pore pressure coefficient, C, and it can be successfully applied to predict the effective stress path in the conventional triaxial stress condition.

(3) The stress-strain relations in undrained condition can be predicted by the hyperbolic equation formulated based on the experimental result that the undrained shear strain is the only function of the stress ratio irrespective of preshear consolidation pressure.

(4) A new incremental stress-strain theory is proposed to calaulate the strains of the normally consolidated clay

in a triaxial stress condition. The proposed pore pressure coefficient, C and equation of the undrained stress path have been incorporated in the new theory to calculate the effective stress increment during loading. The predicted values by the new theory are in good agreement with the observed strains.

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