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A Study on the Model Parameters of the Anisotropic Elastoplastic-Viscoplastic Bounding Surface Model for Cohesive Soils

점성토에 있어서 비등방 점탄소성 Bounding Surface 모델의 모델정수에 관한 연구

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요 지

본 연구에서는 지반의 비등방성을 고려한 점탄소성 bounding surface 모델의 정확성을 검증하고 모델정수의 영향을 고찰하였다. 이를 위하여 모델을 컴퓨터 프로그래밍 하였으며 실내시험을 실시하였다. 실내시험으로는 표준압밀시험, 등방/비등방 압밀 삼축압축시험, 크리프 시험 등이 실시되었다. 연구결과, 컴퓨터 프로그램을 이용한 해석결과와 실내시험 결과는 잘 부합되었으며, 탄소성 모델정수의 영향은 크지 않았으나 점소성 모델정수의 영향은 해석결과에 큰 영향을 미치는 것으로 고찰되었다.

Abstract

In this study, the influence of the model parameters of the anisotropic elastoplastic-viscoplastic bounding surface model was investigated and the model was verified for cohesive soils. The model was implemented into a computer program. Three isotropic, four anisotropic triaxial compression tests, two anisotropic triaxial creep tests, and two oedometer tests were conducted using a well-calibrated equipment. The slurry consolidometer technique was used to obtain very homogeneous and undisturbed specimen. It was observed that the model predictions showed very good agreement with the experimental data. The ranges of the model parameter values have been investigated and it has been observed that the influence of the parameter values on the triaxial results was considerable in the viscoplastic parameters, but not in the elastoplastic parameters.

Keywords : Bounding surface model, Slurry consolidation, Elastoplastic, Viscoplastic

1. Introduction

Field and laboratory investigations have now established that anisotropy significantly influences the stress-strain behavior of soils. Anandarajah and Dafalias (1986) proposed the anisotropic elastoplastic bounding surface model based on its isotropic version suggested by Dafalias and Herrmann (1986) and Dafalias (1986). Elastoplastic theories, however, can not account for time-dependent material behavior. Prediction of time-dependent behavior requires the use of viscoplastic theory. During 1960's, a yield criterion from elastoplastic theory was extended so that it could also account for the time-dependent response. A generalized elastic-viscoplastic theory was developed and popularized by Perzyna (1966).

Al-Shamrani (1991) and Al-Shamrani and Sture (1994) combined the anisotropic elastoplastic bounding surface model (Anandarajah and Dafalias, 1986) and the viscoplastic model (Perzyna, 1966) using its isotropic formulation (Kaliakin and Dafalias, 1990, 1991). An important feature of bounding surface model is that the plastic deformations can occur for the stress states either

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within or on the bounding surface (contrary to the classical plasticity). Also it is possible to have the plastic strain take place immediately on the application of load, and to have a very flexible and smooth variation of the plastic modulus during straining. The anisotropic elastoplastic-viscoplastic bounding surface model, however, has a disadvantage that it needs many model parameters. Model parameters may be as important as model itself.

In this study, isotropic and anisotropic triaxial compression and creep tests, and oedometer test were conducted using a well-calibrated anisotropic triaxial cell and the very homogeneous soil specimens prepared by the slurry consolidometer technique. The model was verified by comparing the experimental results with the model predictions, and the influence of the model parameter values was investigated along with the identification and the calibration of the model parameters.

2. Theoretical Overview of the Model

In the anisotrpic bounding surface model, the stress rate tensor is expressed as the sum of elastic, elastoplastic, and viscoplastic parts. Three hardening rules, i.e., isotropic, rotational, and distortional hardenings, are adopted to consider initial and induced anisotropy. A combination of two ellipses and one hyperbola is used as the bounding surface for better simulation of heavily overconsolidated soils. Fig. 1 shows the concept of bounding surface model. Details on the model are presented in Anandarajah and Dafalias (1986), Al-Shamrani (1991), and Al-Shamrani and Sture (1994).

3. Influence of Model Parameters

For the identification and calibration of the model parameters, and investigation of the effects of varying values of the parameters, the model was implemented into a computer program and laboratory tests were conducted. The laboratory tests are described in the following section. Table 1 shows the model parameters. Subscript c means compression and e means extension. The values of some parameters can be obtained directly from the result of the laboratory test, and some parameters like Patm (atmospheric pressure) and Pl (one-third of Patm) have fixed values, but many other parameter values should be determined from the best results of fitting curves from triaxial tests. Fig. 2 shows the suggested calibration procedure for the model parameter values.

3.1 Traditional Model Parameters

The parameters λ and κ represent the slopes of the

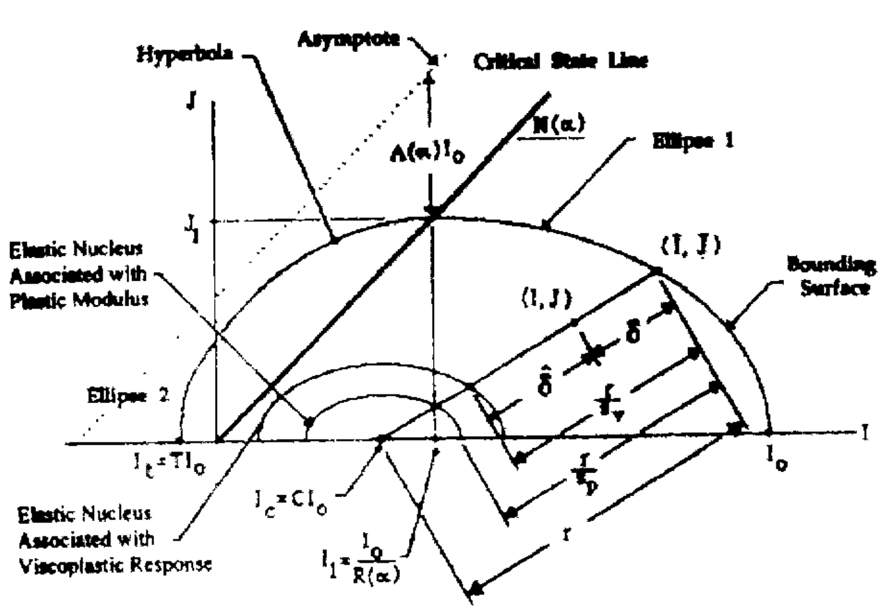

Fig. 1 Schematic illustration of bounding surface model (Kaliakin and Dafalias, 1991)

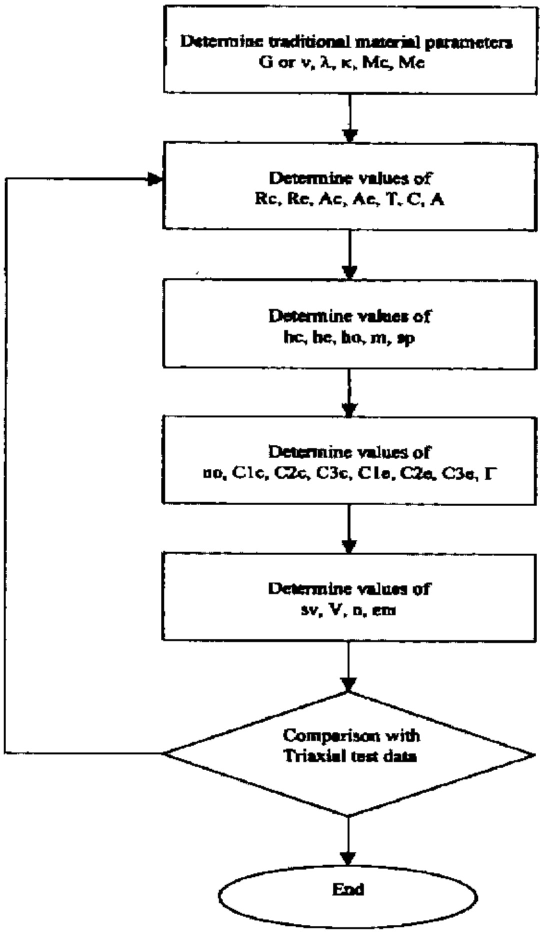

Fig. 2 Suggested calibration procedure for model parameter values

virgin compression line and load/reload line in e-ln p space obtained from oedometer test. The parameter M is the slope of the critical state line in p-q space. The value is determined from triaxial tests carried to ultimate conditions. Due to practical difficulty in triaxial extension test, Me/Mc=0.8 can be assumed (Kaliakin, 1985). The elastic shear modulus G is estimated from the initial slope of a plot of undrained principal stress difference versus axial strain. Poisson's ratio ν is usually assumed to be 0.3 because of practical difficulty of experiment. The transitional stress P_l represents the mean normal effective stress at which a consolidation curve changes from linear in e-ln p space to linear in e-p space. It prevents excessive softening from occurring when the state of a specimen is such that I is small. In all past applications of bounding surface model, Pl has been taken to be equal to one-third of atmospheric pressure.

The combined bulk modulus of pore fluid and soil particles Γ is introduced to enable both drained and undrained conditions to be handled by a single numerical formulation. To model drained condition, Γ must be small enough to prevent the development of any excess pore pressure. To model undrained condition, Γ must be large enough to prevent the occurrence of any volumetric strains (Kaliakin, 1992). DeNatale (1983) suggested 104 Patm -106 Patm for undrained condition.

3.2 Bounding Surface Shape Parameters

The parameter R controling distortional hardening determines the ratio of the major to the minor axes of ellipse 1. The value is determined from the best simulation of the undrained triaxial test. Re/Rc can be assumed to be 0.8 (Al-Shamrani, 1991). The value of R has been in the range 2.0 to 3.0 for isotropic (Kaliakin and Dafalias, 1991) and 2.5 to 4.0 for anisotropic case (Al-Shamrani, 1991), respectively. In this research, the value of R has been found to be in the range 1.5 to 3.0.

The parameters Ac and Ae control the shape of the hyperbolic portion of the bounding surface, which means Ac and Ae are related only to heavily overconsolidated soils. Therefore, they should be determined from the best simulation of triaxial test for heavily overconsolidated specimen. Ae/Ac=0.8 has been usually taken (Al-Shamrani, 1991), and the value of Ac has been in the range 0.02 to 0.2 (Kaliakin and Dafalias, 1991). In this research, the value of Ac has been found to be in the range 0.01 to 0.15.

The parameter T controls the size of the bounding surface in tension side by defining the point at which ellipse 2 intersects the I^a axis. Because T needs to be obtained from extension test but the extension test is rarely performed, T has been fixed at 0.1 (Kaliakin and Dafalias, 1991) or 0.05 (De Natale, 1983). In this research, T was assumed to be equal to 0.05.

The parameter C defines the location of the projection center along the I^a axis. The value of C is determined from the best simulation of triaxial test result. C=0 means that the projection center lies at the origin in stress invariant

Table 1. Model parameters

No.	Parameter	Description	Determination
1	λ	Slope of NCL	Oedometer test
2	κ	Slope of swelling line	
3	Mc	Slope of CSL in compression	
4	Me	Slope of CSL in extension	Triaxial test
5	v or G	Poison's ratio or shear modulus	
6	P_l	Transitional stress	From Patm
7	Patm	Atmospheric pressure	Fixed value
8	Rc	Bounding surface shape parameters	
9	Re		
10	Ac		
11	Ae		
12	T		
13	C		
14	s_p		
15	hc	Shape hardening parameters	
16	he		
17	ho		
18	m		Fitting curves from Triaxial tests
19	A	Anisotropic hardening parameters	
20	no		
21	C_{1c}		
22	C_{2c}		
23	C_{3c}		
24	C_{1e}		
25	C_{2e}		
26	C_{3e}		
27	s_v	Viscoplastic parameters	
28	V		
29	n		
30	ε_m		
31	Γ	Combined bulk modulus	

NCL = Normally Consolidation Line
CSL = Critical State Line

space. C=1 means that the projection center lies at the point of intersection between the I^a axis and ellipse 1. Therefore, C can be any value between 0 and 1. The value of C was found to have a value in the range 0.0 to 1.0 also in this research.

The elastic zone parameter s_p defines the extent of the elastic nucleus and it may have any value over 1. When s_p is 1, the elastic nucleus shrinks to a point, then inelastic deformation occurs immediately on the application of loads. When s_p is infinity, the bounding surface serves as a yield surface as in the classical plasticity, then the behavior of all stress states within the bounding surface is purely elastic. The value of s_p is obtained from the best simulations of triaxial tests. However, thinking that there is no purely elastic response, the value of s_p was assumed to be 1.0 in this research. Fig. 3 and Fig. 4 show the influences of varying R, Ac, C, and s_p on the results of triaxial tests.

3.3 Shape Hardening Parameters

The shape hardening parameters hc, he, ho, and m enter into the equation for the plastic modulus through a shape hardening function. They control the degree to which plastic hardening or softening occurs at stress states within the bounding surface. The values of hc and he are obtained from the best-fit of the results from triaxial tests. The value of hc can be assumed any value over 0, and the value of ho has always been assumed to be equal to the average value of hc and he (Dafalias and Herrmann, 1986). The value of hc has been found to be in the range 10 to 300 in this research. The value of m equal to 0.02 has been used in all past applications of bounding surface model (Kaliakin, 1992), and he/hc=1 was used in this research. Fig. 4 show the effects of varying hc on the results of triaxial tests.

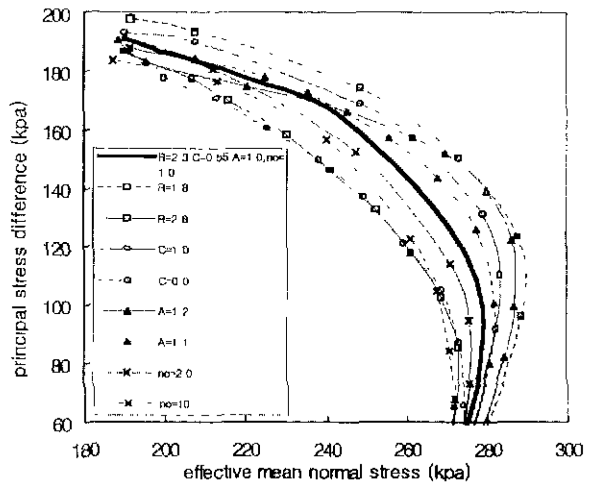

Fig. 3 Effects of varying R, C, A, and no on stress path (OCR=1)

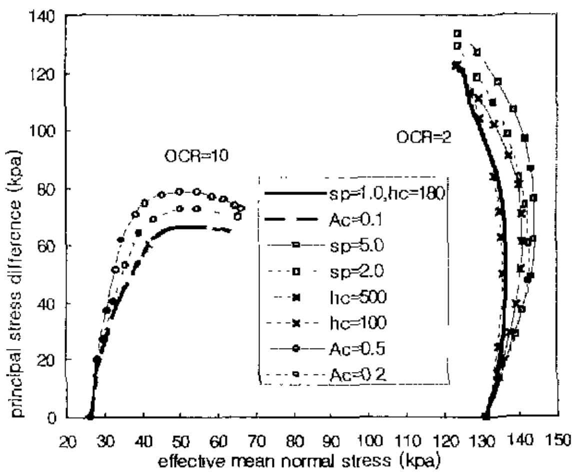

Fig. 4 Effects of varying sp, Ac, and hc on stress path (OCR=2, 10)

3.4 Anisotropic Hardening Parameters

The initial anisotropy parameter A defines the initial rotation of the bounding surface. This initial anisotropy is mainly due to the consolidation mode. The value of A is obtained from the best simulation of the results of triaxial tests. The value of A has been found to be in the range 1.0 to 1.3 in this research. A=1 means initially isotropic state. Fig. 4 shows the effects of varying A on the results of triaxial tests.

The parameters n_o, C_{1c}, C_{2c}, C_{3c}, C_{1e}, C_{2e}, and C_{3e} are related to the induced anisotropy. They contribute to the rotational hardening and the values can be determined from the best-fit of the results of triaxial tests. The values of n_o, C_{1c}, C_{2c}, and C_{3c} have been found to be in the range 0.0 to 20.0, 50 to 150, 0.0 to 10.0, and 10 to 100, respectively, in this research. The values in compression are assumed to be equal to the values in extension. The qualitative influence of no is shown in Fig. 3. Fig. 5 shows the influences of C_{1c}, C_{2c}, and C_{3c}.

3.5 Viscoplastic Parameters

The values of viscoplastic parameters s_v, V, n, and ε_m are determined from the best-fit of the results of undrained triaxial creep test. The values of s_v, V, and n have been found to be in the range 1.0 to 6.0, 10^5 to 10^{10}, and 1.0 to 8.0, respectively, in this study.

The parameter ε_m represents the value of axial strain associated with the time at which the axial strain rate becomes a minimum. If creep rupture is to be predicted analytically, a suitable value for ε_m must be chosen to cause a rapid increase in predicted strain at a given time. If, on the other hand, no evidence of creep rupture is observed experimentally, ε_m should be set equal to an artificially large value like 20 or 30 % (Kaliakin and Dafalias, 1991). Since no creep rupture was observed in the triaxial creep test conducted in this research, the value of ε_m=30 % was assumed. The influences of the values of s_v, V, and n are shown in Fig. 6.

4. Laboratory Test

Three isotropic, four anisotropic consolidated-undrained compression triaxial tests, two anisotropic consolidated-undraind creep tests, and two oedometer tests were conducted according to the method ASTM D4767.

A mixture of 33% kaolin and 67% fine sand by dry weight was used to prepare test specimens. First, the dry soil sample was mixed with deaired water at a water content of twice liquid limit. The slurry was carefully placed into the small slurry consolidometer (Fig. 7), then consolidation was performed using dead weights. Dead weights were applied in four steps considering the slurry state of specimen. Since the diameters of small slurry

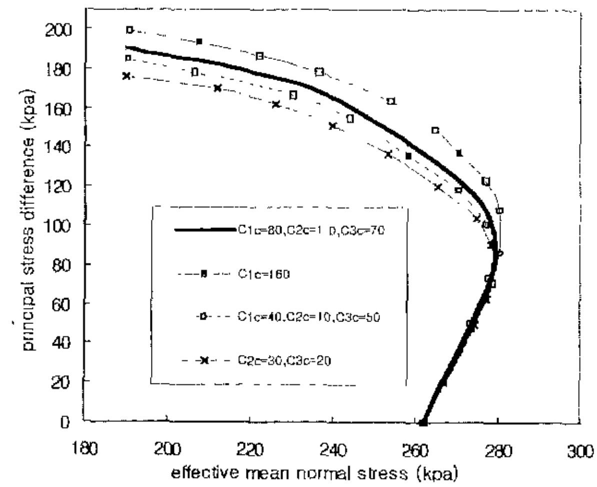

Fig. 5 Effects of varying C_{1c}, C_{2c}, and C_{3c} on stress path (OCR=1)

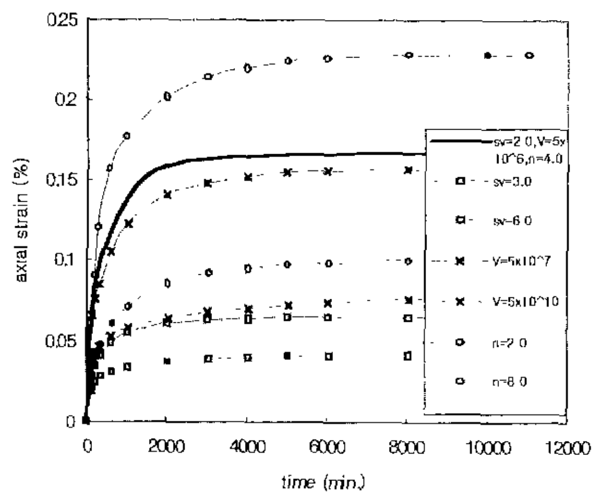

Fig. 6 Effects of varying s_v, V, and n on time-axial strain (OCR=1)

consolidometer and specimen are same, only one side trimming is needed to prepare specimen. Through this slurry consolidometer technique, very homogeneous and undisturbed specimens were prepared with known stress history. The specimen for the oedometer tests were prepared also using the slurry consolidometer technique but with a different size of small slurry consolidometer.

In the triaxial tests, one step was added to the standard procedure to ascertain OC (overconsolidated) state of specimen. Anisotropic consolidation was carried out by applying a vertical stress to the specimen during consolidation in addition to the all-round cell pressure (Fig. 8). The additional vertical stress was applied using a dead weight through the yoke system. The stress ratio 0.42

Fig. 7 Small slurry consolidometer for triaxial test (after Tumay)

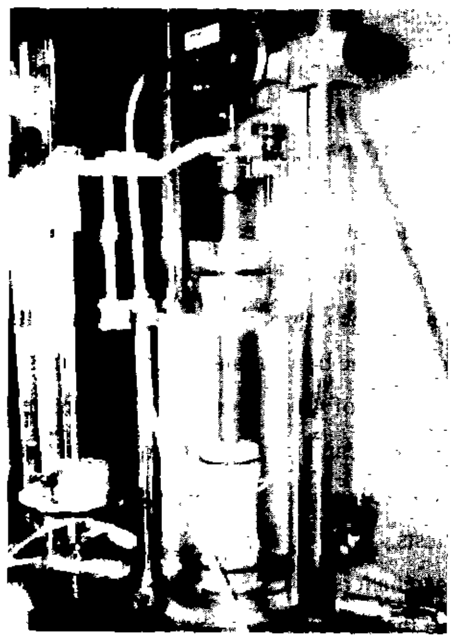

Fig 8 Anisotropic triaxial cell

was used as Ko value as shown in table 2. The value of 0.42 was obtained from the large calibration chamber test, that was conducted under Ko condition and using the same specimen (33% kaolin, 67% fine sand). Details on the chamber test are described in Kurup, et al. (1994). The value of the stress ratio for the step of making specimen overconsolidated state was evaluated using Ko (overconsolidated) = Ko (normally consolidated) x $(OCR)^{1/2}$ suggested by Brooker and Ireland (1965). The undrained compression shearing was conducted at the rate of 0.1%/min. Table 2 shows the triaxial test program.

5. Verification of the Model

The following parameter values were commonly used

Table 2. Triaxial test program

Test No	Slurry Consolid -ometer	Consolidation			Making OC				Undrained shearing or undrained creep
	σv' (kpa)	σv' (kpa)	σh' (kpa)	σh'/σv'	σv' (kpa)	σh' (kpa)	σh'/σv'	OCR	
1	206 85	262 01	262 01	Iso	262.01	262.01	Iso	NC	Undrained shearing (0 1%/min.)
2	206.85	262 01	262 01	Iso	131.01	131 01	Iso	2	Undrained shearing (0 1%/min.)
3	206 85	262 01	262 01	Iso	26 20	26 20	Iso	10	Undrained shearing (0 1%/min.)
4	206 85	262.01	110 04	0.42	262 01	110.04	0 42	NC	Undrained shearing (0 1%/min.)
5	206 85	330 96	139.00	0 42	330 96	139 00	0 42	NC	Undrained shearing (0.1%/min.)
6	206 85	262 01	110 04	0 42	131 01	77 30	0 59	2	Undrained shearing (0 1%/min.)
7	206 85	262 01	110 04	0 42	43 67	43 67	1 0	6	Undrained shearing (0 1%/min.)
8	206 85	262 01	110 04	0 42	262 01	110 04	0.42	NC	Undrained Creep (Δσv=62.74kpa)
9	206 85	262.01	110 04	0 42	43 67	43 67	1.0	6	Undrained Creep (Δσv=68 95kpa)

for the model predictions throughout the whole tests: λ=0.06, κ=0.01, Me/Mc=0.8, T=0.05, Re/Rc=0.8, Ae/Ac=0.8, m=0.02, he/hc=1.0, ho=(hc+he)/2, $C_{1e}/C_{1c}=C_{2e}/C_{2c}=C_{3e}/C_{3c}=1.0$, $\Gamma=5\times10^{5}$, and ε_m=30 %. Table 3 shows the model parameter values used for the model prediction of each triaxial test. The model prediction and the experimental result of each triaxial test are shown in Fig. 9 through Fig. 12. The conditions of the triaxial tests are described in table 2.

In Fig. 9, for isotropic consolidation cases, the model predictions of test 1 (normally consolidated state) and test 2 (OCR = 2), respectively, show good agreement with the experimental data; however, test 3 (OCR = 10) shows disagreement before axial strain 1.8 %. For anisotropic consolidation cases, the model predictions of test 4 to test 6 (both normally consolidated cases) show good agreement with the experimental results. Some disagreement is observed for test 7 (OCR = 6) before axial strain 1.2 %.

In Fig. 10, for normally consolidated cases, the model predictions are matched well with the experimental data for both isotropically (test 1) and anisotropically consolidated cases (test 4 and test 5). The model prediction of test 6 (anisotropic consolidation, OCR = 2) shows very good agreement with the test data. There is some disagreement between the model prediction and test data for test 3 (isotropic consolidation, OCR = 10), but for test 7 (anisotropic consolidation, OCR = 6), the model prediction and test result show good agreement.

In Fig. 11, for all cases, the model predictions show good agreement with the experimental results. Especially, the lightly consolidated cases for both isotropic (test 2) and anisotropic consolidations (test 6) show very good agreement.

6. Summary and Conclusions

The anisotropic elastoplastic-viscoplastic bounding surface model has been verified and the influence of the model parameters has been investigated using the computer program and the laboratory test results. The slurry consolidometer technique was proven to be effective in obtaining very homogeneous and undisturbed cohesive specimens with known stress history.

In this study, the values of the bounding surface shape parameters R, Ac, C have been found to be in the range 1.5 to 3.0, 0.01 to 0.15, 0.0 to 1.0, respectively. The values of the shape hardening parameter hc and the initial anisotropic parameter A have been found to be in the range 10 to 300 and 1.0 to 1.3, respectively. The values of the anisotropic hardening parameters n_o, C_{1c}, C_{2c}, and C_{3c} have

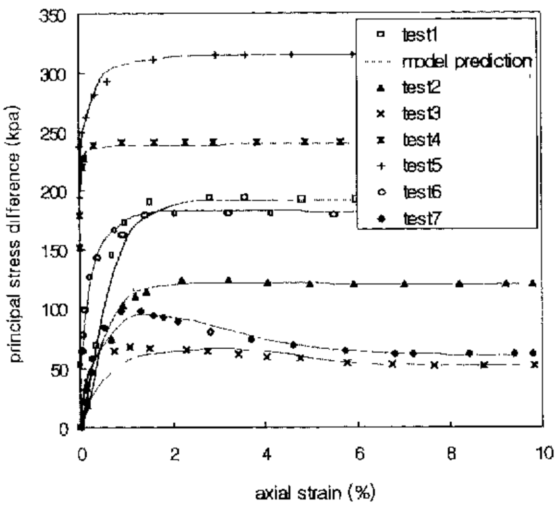

Fig. 9 Model prediction and triaxial test results of axial strain-principal stress difference

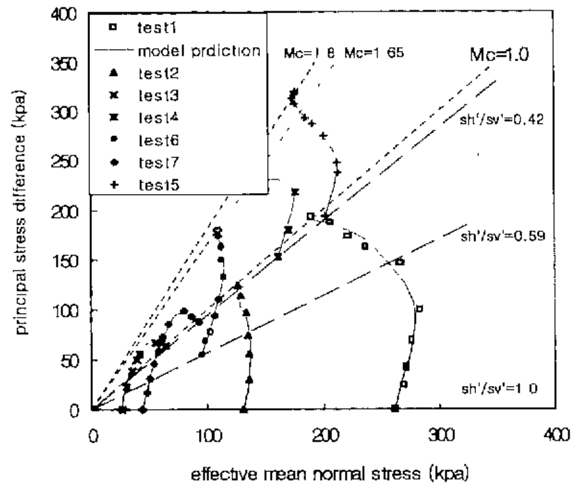

Fig. 11 Model prediction and triaxial test results of stress path

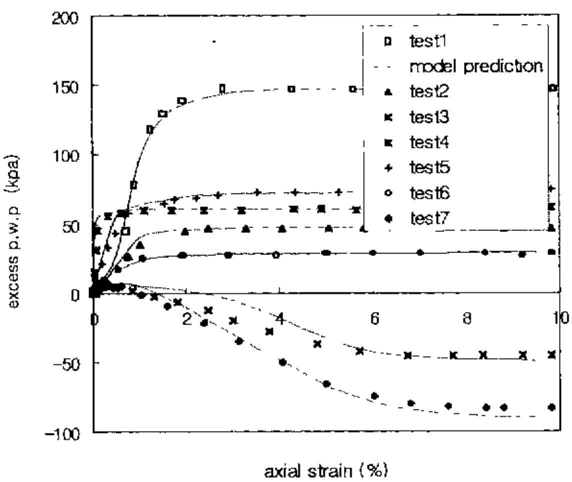

Fig. 10 Model prediction and triaxial test results of axial strain-excess p.w.p

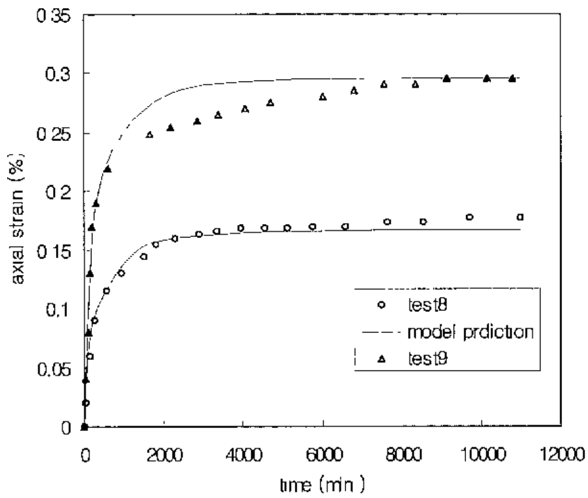

Fig. 12 Model prediction and creep test results of time-axial strain

Table 3. Model parameter values for the triaxial tests

모델정수	test1	test2	test3	test4	test5	test6	test7	test8	test9
Mc	1.0	1.0	1.8	1.8	1.8	1.65	1.0	1.8	1.8
G(kPa)	9500	9000	15000	15000	14000	15500	15000	15000	14500
Rc	2.3	2.2	2.0	2.0	1.9	2.0	2.1	1.9	2.0
Ac	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
C	0.55	0.5	0.6	0.6	0.7	0.7	0.8	0.7	0.7
s_p	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
hc	190	180	190	190	200	160	130	180	130
A	1.0	1.0	1.2	1.2	1.2	1.2	1.0	1.2	1.0
n_o	1.0	1.0	1.0	1.0	1.0	1.0	8.0	1.0	7.0
C_{1c}	80.0	90.0	80.0	80.0	80.0	80.0	70.0	80.0	80.0
C_{2c}	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C_{3c}	70.0	60.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
s_v								2.0	2.0
V(x10^6)								5	5
n								4.0	4.0

been found to be in the range 0.0 to 20.0, 50 to 150, 0.0 to 10.0, and 10 to 100, respectively. The values of the viscoplastic parameters sv, V, and n have been found to be in the range 1.0 to 6.0, 10^5 to 10^{10}, and 1.0 to 8.0, respectively.

The results of the simulated triaxial tests were not so much influenced by the variation of the elastoplastic parameter values as shown in Fig. 3 to Fig. 5. On the other hand, the values of the viscoplastic parameters considerably affected on the creep results as shown in Fig. 6.

It was observed that the model predictions showed very good agreement with the experimental data for all cases, i.e., isotropic, anisotropic, normally consolidated, lightly consolidated, and heavily overconsolidated cases both for the triaxial compression and triaxial creep loading regimes; however, the model needs many model parameters; therefore, the reduction of the number of model parameters may be needed in keeping with the capability of the model.

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