Evaluation of OCR in Fine Grained Soil by Piezocone Tests
피에조콘 관입 시험에 의한 OCR 평가

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개 요 : 본 연구의 목적은 Piezocone 관입시험을 이용한 연약지반의 OCR 평가에 있어 기존의 여러 가지 해석방법들과 최근에 새롭게 제안된 방법들을 실내 모형토조에서 실측된 피에조콘 관입 실험치에 적용하여 각 해석방법들의 차이와 장단점들을 비교 분석하는데 있다. 본 연구의 연구실험방법으로는, Piezocone 관입을 위한 연약 모형지반 조성을 위하여 초대형 Slurry Consolidometer에 Free Stress 상태의 Slurry를 45일간 압밀시킨후 Automatic Computer Control Calibration Chamber (LSU/CALCHAS; Louisiana State University Calibration Chamber System)에 옮긴후 다시한번 압밀시키는 Two-Stage Consolidation Method를 사용하였다. 모형지반은 여러 가지 Boundary Condition들과 Stress Condition 그리고 Stress History등을 달리하여 총 5개의 지반을 조성하였다. 관입시험은 총 25개의 Piezocone 관입이 수행되어졌고, 그중 4개는 Standard 10 cm2 Piezocone이고, 나머지 21개는 Miniature Piezocone이 사용되었다. Piezocone 실험치들에 대한 여러 가지 OCR 해석방법 적용결과, Schmertmann방법은 5개 모형지반 모두에서 과다한 OCR평가를 보였으며, B_q 방법은 일부모형지반에서 음의 OCR값으로 계산되어졌다. 그러나, Critical-State Soil Mechanics 와 Cavity Expansion 이론에 근거하여 Mayne(1991), Kurup(1993), Tumay et al (1995) 들이 제안한 OCR 평가방법들은 실험치와 잘맞는 경향을 보여주었다. 이와같은 이론 모델값들의 차이는 응력조건(Stress Condition)과 경계조건(Boundary Condition)들에 대한 각 해석방법들의 고려정도에 따른 결과로 판단된다.

KEY WORDS : OCR, Piezocone, Critiacl-State Soil Mechanic, Calibration Chamber, Pore pressure ratio.

1. INTRODUCTION

The overconsolidation ratio (OCR) defined as the ratio of the preconsolidation pressure, p, and the existing effective overburden pressure, σ'_{vo}, is an important factor governing the strength, stress-strain behavior, and the compressibility characteristics of soils. Knowledge of the OCR is hence essential in selecting relevant soil parameters for a proper design of geotechnical systems. The conventional method of determining OCR is from laboratory oedometer tests on undisturbed samples obtained from the field.

The determination of p is influenced by the type and procedure of testing (Crawford, 1964) and also by the unavoidable sample disturbance. If a continuous profile of OCR with depth is required, the conventional laboratory method becomes time consuming and expensive, requiring an elaborate testing scheme. In recent years, the estimation of OCR from piezocone has gained a lot of attention.

2. INTERPRETATION METHOD

The use of piezocone for estimating OCR have been suggested by a number of researchers (Schmertmann, 1978; Baligh, et al., 1980; Tumay, et al., 1982; Senneset, et al., 1982, 1988; Wroth, 1984; Robertson, et al., 1986; Konrad and Law, 1987; Mayne, 1987; Mayne and Holtz, 1988; Mayne and Bachus, 1988; Sully et al., 1988; Sandven, et al., 1988; Mayne, 1991, 1992). Some of the suggested interpretation methods are evaluated using the chamber piezocone obtained in this study.

2.1 SCHMERTMANN METHOD

The cone resistance q_T has been recognized as a measure of the undrained shear strength s_u which itself is a function of the OCR (Ladd, et al., 1977; Schmertmann, 1978). Hence, the cone resistance should reflect the OCR of the soil deposit. Based on the above argument, Schmertmann (1978) suggested the following method to estimate OCR:

(1) Using the relationship proposed by Skempton (1957), estimate the normalized, normally consolidated undrained shear strength, i.e.:

$$s_1 = \left(\frac{s_u}{\sigma'_{v0}}\right) = 0.11 + 0.0037 I_p \qquad (2.1)$$

where I_p is the plasticity index.

(2) From the corrected cone resistance, q_T, calculate

$$s = \frac{s_u}{\sigma'_{v0}} = \frac{\left(\dfrac{q_T - \sigma_{v0}}{\sigma'_{v0}}\right)}{N_{kT}} \qquad (2.2)$$

where σ_{vo} is the total overburden pressure and N_{kT} is the cone factor.

(3) Estimate OCR using the relationship

$$OCR = \left(\frac{s}{s_1}\right)^{1.13 + 0.04\left(\frac{s}{s_1}\right)} \qquad (2.3)$$

2.2 PORE PRESSURE PARAMETER

$$B_q = \frac{u - u_0}{q_T - \sigma_{v0}}$$ Senneset and Janbu (1984), (2.4)

where u = pore pressure at the cone base, u_o = equilibrium pore pressure, u = u - u_o = excess pore pressure, and σ_{vo} = total overburden pressure. It is the shear induced pore pressure that reflects the stress history of the soil and any pore pressure parameter used to estimate OCR should relate a change in the pore pressure to changes in the octahedral and shear stress around a penetrating cone (Wroth, 1984). Because of the similarity between B_q and the Skempton's pore pressure parameter at failure (A_f) (Skempton, 1954), B_q was considered as a promising parameter to estimate OCR. The following expression was suggested

$$OCR = \frac{2.3B_q}{(3.7B_q - 1)} \quad (2.5)$$

As mentioned earlier, it is the shear induced pore pressure that reflects the stress history of the soil. The B_q method was considered a promising parameter to evaluate the OCR. However, this method does not allow the shear induced pore pressures to be separated from those generated by the octahedral stresses. Research performed by various investigators (Battaglio, et al., 1986; Campanella, et al., 1986) have shown that no universal correlation exists between B_q and OCR. Moreover, in soft clays, the accuracy of tip resistance may be considered unreliable (Tumay and Acar, 1985). The existence of a large pore pressure gradient around the tip especially in overconsolidated clays has been pointed out by a number of investigators (Baligh, et al., 1981; Tumay, et al., 1982; Campanella, et al., 1986). Using this principle, Sully, et al. (1988) suggested the following possible pore pressure parameters to predict OCR.

(1) Pore pressure ratio (PPR)

$$PPR = \frac{u_1}{u_2} \quad (2.6)$$

(2) Excess pore pressure ratio (PPR1)

$$PPR1 = \frac{(u_1 - u_0)}{(u_2 - u_0)} \quad (2.7)$$

(3) Pore pressure difference (PPD)

$$PPD = \frac{(u_1 - u_2)}{u_0} \quad (2.8)$$

2.3 CAVITY EXPANSION/MODIFIED CAM-CLAY METHODS

Using the critical-state soil mechanics and the cylindrical cavity expansion theory

Mayne (1987) and Mayne and Holtz (1988) suggested the following expression for determining OCR

$$OCR = \left(0.317\frac{\Delta u}{\sigma'_{v0}}\right)^{1.79} \qquad (2.9)$$

where Δu is the excess pore pressure measured immediately behind the cone tip. Mayne (1991, 1992) also suggested the following expressions for predicting OCR using the Cavity Expansion/Modified Cam-Clay (CE/MCC) approach:

$$OCR = 2\left[\frac{1}{1.95M+1}\left(\frac{q_T - u_{bt}}{\sigma'_{v0}}\right)\right]^{1.33} \qquad (2.10a)$$

$$OCR = 2\left[\frac{1}{1.95M}\left(\frac{q_T - u_T}{\sigma'_{v0}}+1\right)\right]^{1.33} \qquad (2.10b)$$

where u_{bt} = u_2 = pore pressure measured just above the cone base and u_T = u_1 = pore pressure measured on the tip.

2.4 KURUP METHOD

The methods proposed by Mayne (1991, 1992) was developed based on the spherical cavity expansion theory of Vesic (1975) which has been formulated for the octahedral normal stress (σ_o = σ_{oct}). In the equation proposed by Mayne (equation 2.10a), σ_o has been taken equal to σ_{vo} since the in-situ lateral stress is difficult to determine. The method proposed by Kurup (1993) and Tumay, et. al., (1995) utilizes the technique of Ko profiling suggested by Sully and Campanella (1991) and is combined with equation 2.10a (after substituting for σ_o = σ_{oct} instead of σ_o = σ_{vo}). The resulting expression for OCR is given by

$$OCR = 2\left[\frac{3}{(1.95M+1)\sigma'_{v0}}\left(\frac{q_T - u_2}{1+2K_0}\right)\right]^{1.33} \qquad (2.11)$$

or in terms of ul and u2

$$OCR = 2\left[\frac{3}{(1.95M+1)}\left(\frac{q_T - u_2}{\sigma'_{v0}(1+2a)+2b(u_1-u_2)}\right)\right]^{1.33} \qquad (2.12)$$

The values of 'a' and 'b' suggested by Sully and Campanella may be used for in-situ predictions of OCR.

3. TESTS

In this study, miniature piezocone penetration tests and reference piezocone tests were conducted in calibration chamber (LSU/CALCHAS). Two main phases are used in the test procedure. They are the specimen preparation phase and the penetration phase. The stage of specimen preparation consists of two steps: slurry consolidation in consolidometer, reconsolidation in calibration chamber. Each procedure is involved with heavy instrumentation which provide detailed monitoring of the specimen environment.

Soil slurry(K-33 specimen) was prepared by mixture of 33 % kaolin, 67 % Edgar fine sand and de-aired water by weight. The grain size distribution of the kaolin, fine sand and soil mixture(K-33 specimen) is shown in Figure 1. The Atterberg limits of the virgin kaolin, fine sand and K-33 mixture are shown in Table 1.

Five specimen were prepared by the technique descrived above. Summary of the stress history of the each specimen and reference soil parameters are shown in Table 2 and Table 3. All tests were conducted at the standard penetration rate of 20 mm/sec. The general view of data acquisition system set up for calibration chamber test is shown in Figure 2. Two kinds of miniature piezocones were utilized for this research (Figure 3).

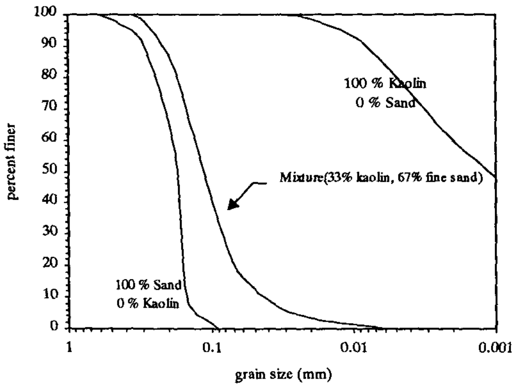

Figure 1 Particle size distribution curves

Soil	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Specific Gravity (G_s)
Kaolinite	54	28	26	2.66
Fine Sand	....	....	....	2.67
Kaolinite and Sand (K33)	20	14	6	....

Table 1 Properties of Kaolin and K-33 mixture

Specimen No.	Chamber Consolidation	OCR	Final Effective Stresses (Kpa)		Lateral Stress Coefficent (K_0)
			Vertical	Horizontal	
1	Isotropic	1	207	207	1
2	Anisotropic (K_0)	1	207	86.2	0.42
3	Isotropic	1	262.2	262.2	1
4	Anisotropic (K_0)	1	262.2	104.8	0.40
5	Anisotropic (K_0)	10.9	24.2	40.71	1.70

Table 2 Summary of the stress history of the chamber specimens

Specimen No.	Water Content (%)	Undrained Shear Strength S_u (Kpa)	Skempton pore pressure parameter at failure, A_f	Rigidity Index $I_r = G_{50}/S_u$	Radial Coefficient of Consolidation (c_r x 10^{-3} cm²/sec)
1	17.36	80	0.49	100	1.9
2	19.43	65	0.37	333	4.2
3	17.22	98	0.71	167	2.2
4	17.54	121	0.25	400	4.2
5	16.80	35	-0.02	500	1.8

Table 3 Reference soil parameters

Table 4 gives the summary of the cone penetration test schedule. Each penetration is identified with a Test ID which specifies pertinent characteristics about : (1) specimen number, (2) boundary condition, (3) stress condition, (4) test repetition at different location (if applicable), (5) cone penetrometer manufacturer, (6) cone type - U configuration, (7) piezocone projected area, and (8) location of penetration. The detailed legend for Test ID is given in Table 5.

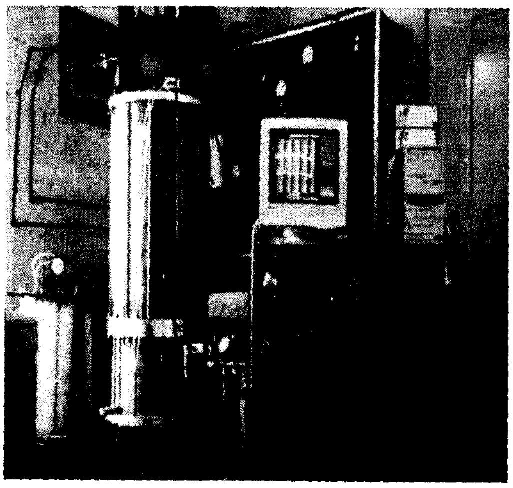

Figure 2 General view of data acquisition system set up

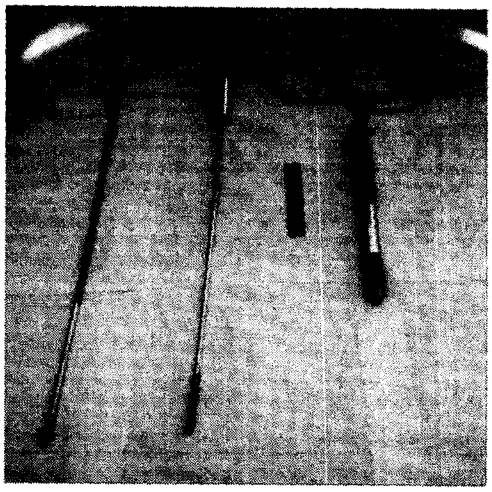

Figure 3 Cone Penetrometers

Specimen No.	Test ID	Boundary Condition	Filter Location: U_1 on cone face	Filter Location: U_2 Config 0.5 mm above cone base	Filter Location: U_1 Config at cone Tip	Location of Penetration: Center (location 0)	160 mm from center (location 1)	177 mm from center (location 2)	160 mm from center (location 3)	75 mm from center (location 4)
1	1_{BI} FR10	1	X			X				
	1_{BI} F1O1	1			X		X			
	1_{BI} F1O2	1			X			X		
	1_{BI} F1O3	1			X				X	
	1_{BI} F1O4	1			X					X
2	2_{AN} FR10	3	X			X				
	2_{AN} F2N1	3		X			X			
	2_{AN} F1O2	3			X			X		
	2_{AN} F2O4	3		X						X
	2_{AN} F2O3	3		X					X	
3	3_{BI} FR10	1	X			X				
	3_{BI} F2N1	1		X			X			
	3_{BI} F1O2	1			X			X		
	3_{BI} F2O3	1		X					X	
	3_{BI} F1O4	1			X					X
4	4_{AN} F2N0	3		X		X				
	4_{AN} F1N1	3			X		X			
	4_{AN} F2N2	3		X				X		
	4_{AN} F1O3	3			X				X	
	4_{AN} F2O4	3		X						X
5	5_{AN} FR10	3	X			X				
	5_{AN} F2N1	3		X			X			
	5_{AN} F1N2	3			X			X		
	5_{AN} F1O3	3			X				X	
	5_{AN} F2O4	3		X						X

Table 4 Summary of the cone penetration test locations

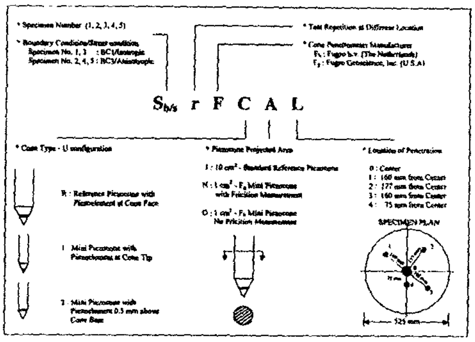

Table 5 Legends for Test ID

4. TEST RESULTS

The penetration testing program for this study was achieved with a total 5 large size cohesive specimens on two different stress conditions (isotropic and anisotropic, Table 2). In the penetration profiles in specimen 1(Figure 1), the steady values of corrected net tip resistance (q_T - u_0) have been obtained after reaching some depth (approximately 10cm). Although few of the excess pore pressure profiles ($u = u_T - u_0$) during the penetration exhibited poor response, in general there was a trend to approach a steady value. Summary of the cone penetration test results and dissipation depths are given in Table 6.

5. EVALUATION OF THE INTERPRETATION METHODS

The estimated OCR from the chamber PCPT data, using the earlier mentioned interpretation methods are given in Table 7. The method proposed by Schmertmann data (1978) overestimated the OCR for all the specimens. Sully, et al. (1988) have suggested

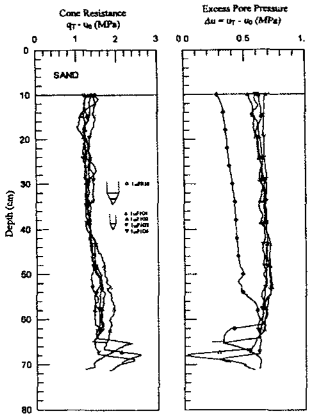

Figure 3 Penetration profiles in specimen 1 (See Table 5 for Test No. Identification)

Specime No.	Stress Condition	Stress History	Test	Tip Resistance, $q_T - u_0$ (Kpa) Average	Tip Resistance Standard Deviation	Excess Pore Pressure, Δu (Kpa) Average	Excess Pore Pressure Standard Deviation	Dissipation Depth (cm)
1	Isotropic	OCR=1	1_{IA} FR10	1234.8	116.9	418.3	76.4	64.7
			1_{IA} F1O1	1186.1	381.5	618.5	108.1	66.5
			1_{IA} F1O2	1242.1	141.8	665.9	26.7	.....
			1_{IA} F1O3	1375.8	85.7	668.0	14.4	67.2
			1_{IA} F1O4	1192.9	138.8	643.9	33.6	61.9
2	Anisotropi (Ko)	OCR=1	2_{MA} FR10	1136.6	28.1	274.1	35.6	25.9
			2_{MA} F2N1	1182.1	11.4	.	. .	.
			2_{MA} F1O2	1180.7	16.6	467.0	20.0	54.2
			2_{MA} F2O4	1321.1	63.9	490.1	24.1	64.0
			2_{MA} rF2O3	1194.0	61.8	475.7	10.2	58.0
3	Isotropic	OCR=1	3_{IA} FR10	1434.7	53.1	.....	. .	57.6
			3_{IA} F2N1	1514.9	23.9	778.7	110.6	59.3
			3_{IA} F1O2	1539.9	33.8	793.6	26.3	55.4
			3_{IA} F2O3	1512.5	34.4	...	..	…
			3_{IA} F1N4	1559.9	108.3	.....	.....	.
4	Anisotropi (Ko)	OCR=1	4_{MA} F2N0	1406.8	23.4	517.4	27.5	51.7
			4_{MA} P1N1	1412.2	114.4	....	.....	...
			4_{MA} rF2N2	1329.9	91.4	527.7	36.9	55.5
			4_{MA} F1O3	1335.4	30.4	535.0	58.3	59.8
			4_{MA} F2O4	1373.3	41.4	598.3	17.5	60.1
5	Anisotrope (Ko)	OCR=10.9	5_{MA} FR10	1039.5	26.2	266.9	54.1	63.9
			5_{MA} F2N1	1067.0	17.6	243.4	57.9	51.2
			5_{MA} P1N2	1041.0	35.1	....	.....	.....
			5_{MA} F1O3	1097.0	33.2	308.1	7.4	70.6
			5_{MA} F2O4	1077.7	29.6	288.7	10.4	55.0

Table 6 Summary of the cone penetration test results

Table 7 Interpretation of OCR from PCPT data

Specimen No.	OCR	Predicted OCR: Schmertmann (1978)	Bq Method	Sully et al. (1988)	Mayne (1987)	Mayne (1992)	Kurup & Tumay (1993, 1995)
1	1	4.1	.....	.....	1	1.8	.....
2	1	5.3	1.3	0.4	0.6	1.5	2.8
3	1	3.8	1.1	0.6	0.9	1.2	1.2
4	1	4.7	1.4	0.4	0.5	1.4	2.8
5	10.9	40.8	-9.7	3.4	10.1	28.6	17.2

an interesting method to estimate OCR using pore pressure parameters determined from pore pressure measurements at the cone face and above the cone tip. For using the PPD method, the pore pressure filter location, height and thickness have to be standardized since these can significantly affect the magnitude of the measured pore pressure. The predicted OCR's using the methods suggested by Mayne (1987) and Mayne (1991, 1992) are shown in Table 7. These prediction methods have been formulated from the theories of cavity expansion and critical-state soil mechanics. The method proposed by Mayne (1987) using the excess pore pressure measured above the cone base gave good predictions of the OCR. The method suggested by Mayne (1992) gave good predictions of OCR for pore pressures measured above the cone base except specimen 5. Interpretation using pore pressures measured at the cone tip overestimated the OCR's. The method proposed by Kurup (1993) and Tumay, et. al., (1995) provide better prediction of OCR than Mayne (1992) in specimen 5. The reason probably is due to consideration of influence of lateral stress on stress history.

6. CONCLUSION

The method proposed by Schmertmann overestimated the OCRs of all five specimens by a factor of almost four. The B_q method yielded a negative value for the OCR in specimen 5. Research performed by various investigators in the past have shown that no universal correlation exists between Bq and OCR. The method proposed by Sully et al. underestimated the OCRs of all five specimens. The equation proposed by Mayne (1987) that makes use of the excess pore pressure above the cone base (u_2 filter location) was found to give very good OCR predictions in all five specimens. However it should be mentioned that this method will predict a negative OCR in heavily overconsolidated stiff clays, when negative excess pore pressure develop at the u_2 filter location. The OCR prediction methods based on critical-state soil mechanics and cavity expansion theories proposed by Mayne (1991, 1992), Kurup (1993), Tumay et al. (1995) were found to give acceptable OCR predictions. The overprediction can be attributed to the penetration boundary condition BC3 (zero lateral strain and constant vertical stress) that appears to develop a stiff specimen response, thereby yielding a higher corrected cone resistance q_T, and high predicted OCR values.

7. REFERENCES

1. de Lima, D. C., 1990, "Development, Fabrication and Verification of the LSU In Situ Testing Calibration Chamber," Ph.D. Dissertation, Louisiana State University, Baton Rouge, LA, 340 p.
2. Kurup, P. U., Calibration Chamber Studies of Miniature Piezocone Penetration Tests in Cohesive Soil Specimens, Ph. D. Dissertation, Louisiana State University, Baton Rouge, LA., May 1993, pp. 258.2.
3. Mayne, P. W. and Bachus, R. C., 1988, "Profiling OCR in Clays by Piezocone Soundings," Proceedings, 1st International Symposium on Penetration Testing, Orlando, Vol. 2, pp. 857-864.3.
4. Mayne, P. W., 1991, 1992, "Determination of OCR in Clays by PCPT using Cavity Expansion and Critical State Concepts, " Soils and Foundations, Vol. 31, No. 2, pp. 65-76 and Closure, Vol. 32, No. 4, pp. 190-192.4.
5. Schmertmann, J. H., 1978, "Guidelines for Cone Penetration Test," United States Department of Transport, Report FHWA TS-78-209, 145 pp.5.
6. Sully, J. P., Campanella, R. G. and Robertson, P. K., 1988, "Overconsolidation Ratio of Clays from Penetration Pore Pressures," ASCE Journal of Geotechnical Engineering Division, Vol. 114, No. 2, pp. 209-216.6.
7. Tumay, M.T., Kurup, P.U., and Voyiadjis, G. Z., Profiling Lateral Stress Coefficient and Overconsolidation Ratio from Piezocone Penetration Tests, Porceedings, International Symposium on Cone Penetration Testing, CPT95, Linkoping, Sweden, October 1995, pp. 337-342.