Distribution of Excess Porepressure caused by PCPT into OC clay

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ABSTRACT : This paper presents the results of an analysis of the excess porewater pressure distribution due to piezocone penetration in overconsolidated clays. From piezocone test results for moderately and heavily overconsolidated clays, it was observed that the excess porewater pressure increases monotonically from the piezocone surface to the outer boundary of the shear zone and then decreases logarithmically to the outer boundary of the plastic zone. It was also found that the size of the shear zone decreases from approximately 2.2 to 1.5 times the cone radius with increasing OCR, while the plastic radius is about 11 times the piezocone radius, regardless of the OCR. The equation developed in this study based on the modified Cam clay model and the cylindrical cavity expansion theory, which take into consideration the effects of the strain rate and stress anisotropy, provide a good prediction of the initial porewater pressure at the piezocone location. The method of predicting the spatial distribution of excess porewater pressure proposed in this study is based on a linearly increasing Δu_{shear} in the shear zone and a logarithmically decreasing Δu_{oct}, and is verified by comparing with the excess porewater pressure measured in overconsolidated specimens at the calibration chamber.

Keyword : porewater pressure, cone penetration, overconsolidated soils, laboratory test

1. INTRODUCTION

From the piezocone dissipation test in the heavily over-consolidated cohesive soils, the standard piezocone (u_2 type) frequently shows an increase in the excess porewater pressure from the initial value to a maximum, followed by a decrease to the hydrostatic value during the dissipation test (Lunne et al. 1986; Battaglio et al. 1986; Sully et al. 1988; Chen and Mayne 1994). It is well known that a negative porewater pressure is induced near the piezocone, due to the dilative characteristics of over-consolidated soils, and the dissipation of this negative pressure increases the porewater pressure until it reaches a maximum value (Kiousis et al. 1988). Although several consolidation-time models are currently available to describe the dissipation behavior of clay, no model has been able to rationally explain the dilatory response of stiff clays except for that of Burns and Mayne (1998).

The spatial distribution of the initial excess pore pressure is decided by the zone of influence and the magnitude of porewater pressure induced by piezocone penetration. The zones of influence, such as the plastic or shear zone, are induced by the piezocone penetration, and the excess pore pressure within these zones can be divided into the octahedral and shear components. While the octahedral component of the excess porewater pressure (Δu_{oct}) is positive in most cases, the shear component (Δu_{shear}) can be positive at a low over-consolidated ratio (OCR) or negative at a high OCR. Moreover, the properties, such as the rigidity index (I_r), and undrained shear strength, obtained from general laboratory test should be corrected by considering the piezocone penetration rate. The shear strength and modulus vary with the strain rate applied and tend to increase with increasing strain rate.

In this paper, theoretical expressions for the radial distribution of the excess porewater pressure due to the piezocone penetration are developed using the hybrid cavity expansion - modified Cam clay model, while taking into consideration the anisotropic stress condition and strain rate. The sizes of the shear and plastic zones are evaluated from the porewater pressures measured during the piezocone penetration into cohesive specimens, which are produced with various OCRs by means of a calibration chamber system. Also, the spatial distributions of the porewater pressure predicted for various OC clays are compared with the data measured by the piezocone and piezometers in the calibration chamber system.

2. PREVIOUS STUDIES

2.1 Spatial Distribution of Excess Porewater Pressure

The magnitude of the excess porewater pressure induced due to piezocone penetration into the ground is significantly affected by the shape, size and geometry of the penetrometer, shear strength and stiffness of the surrounding soil, stress history, etc. The zones influenced by the cone penetration are composed of the shear zone and the plastic zone. The shear zone is the area in which the soil reaches the critical state due to its large shear strain, and the magnitude of the excess porewater pressure in this zone is significantly affected by its dilative response during shear. The plastic zone, which is formed outside the shear zone, is the area in which the excess pore pressure is affected by the volumetric strain and the magnitude of the excess pore pressure in this zone is positive in most cases.

Gupta (1983) assumed spherical symmetry below the piezocone and cylindrical symmetry along the cone shaft. The dimension of the shear zone was assumed to be about four times the cone radius. The logarithmic distribution of the negative excess pore pressures in the shear zone and the cubic distribution of the positive excess pore pressure in the plastic zone were also assumed. Burns and Mayne (1998) evaluated the size of the plastic zone using spherical cavity expansion theory, and the size of the shear zone by regression analysis, assuming a linear decrease in the excess pore pressure with increasing distance from the cone body. Kurup and Tumay (1997) also showed that the initial excess pore pressure distributions in the influence zones evaluated by a number of theoretical methods are quite different from the measured values.

In overconsolidated clays, the magnitude of the excess porewater pressure generated in the shear zone due to the piezocone penetration governs the initial response of the non-standard dissipation curve. Vesic (1972), Gupta (1983), and Burns and Mayne (1998) suggested that the size of the shear zone is independent of the OCR. And Abu-Farsakh et al. (1998) showed by numerical analysis on miniature piezocone tests that the size of the shear zone is dependent on the OCR and that the shearing of the OC specimen is localized in a smaller zone than that in the NC specimen.

2.2 Effect of the Initial Stress on the Piezocone Porewater Pressure

Burns and Mayne (1998) used the hybrid cavity expansion theory to derive an expression for the piezocone porewater pressure in the form of the decoupled octahedral normal and shear components. In this approach, the mean effective stress was assumed to be equal to the effective vertical stress and the effect of the initial anisotropic stress state was neglected. Chang et al. (1999) used the modified Cam clay model to evaluate the porewater pressure of the piezocone, incorporating the effect of stress history. Since the stress state of natural soil is anisotropic, care has to be taken when using the modified Cam clay model, and numerous attempts to accomplish this have been made by several researchers (Wroth 1984; Wood 1990; Chang et al. 1999).

2.3 Effect of Strain Rate on Piezocone Porewater Pressure

The penetration rate of 20mm/sec in the standard piezocone test is much faster than the strain rate in the triaxial compression test conducted in the laboratory. Therefore, in order to predict the excess pore pressure induced by the piezocone penetration, the effect of the strain rate on the undrained shear strength should be taken into consideration. Ladd and Foott (1974) observed that each log cycle of the strain rate is accompanied by a 10% increase in the undrained shear strength. Kulhawy and Mayne (1990) proposed a factor that could be used to correct the shear strength with respect to the strain rate:

$$\alpha_{\varepsilon} = \frac{s_u}{(s_u)_{\dot{\varepsilon}=1\%/hr}} = 1.0 + 0.1\log\dot{\varepsilon} \tag{1}$$

where α_ε is the correction factor for the strain rate, s_u is the undrained shear strength at strain rate $\dot{\varepsilon}$, and $(s_u)_{\dot{\varepsilon}=1\%/hr}$ is the reference undrained shear strength at a strain rate of 1%/hr.

In order to predict the excess porewater pressure induced by the piezocone penetration, Chen and Mayne (1994) assumed the strain rate of cone penetration to be about 200,000%/hr, while Chang et al. (2001), taking the spherical cavity strain rate into account, suggested a strain rate of 800,000%/hr. According to Eq. 1, the range of the equivalent strain rate associated with cone penetration suggested above means that the undrained shear strength evaluated by the piezocone test is 53-59% larger than that determined from the isotropically consolidated undrained (CIU) triaxial test with the reference strain rate. However, Ladanyi (2002) suggested that the undrained shear strength corrected for the effect of the strain rate was 12-15% higher than that obtained at the reference strain rate, which is lower than the values reported by Chen and Mayne (1994) and Chang et al. (2001). Chang et al. (2001) also provided the equation to predict the piezocone porewater pressure by introducing the correction factor, α_{ε}.

3. EXPERIMENTAL STUDY

3.1 Korea University Calibration Chamber System (KUCCS)

A large calibration chamber system with a two-stage consolidation technique was designed on the basis of the Louisiana State University Calibration Chamber System (LSU/CALCHAS) (de Lima, 1990) and fabricated at Korea University. This system is composed of a slurry consolidometer, a calibration chamber, a control system, and a data acquisition system, as shown in Figure 1. The calibration chamber, which houses a specimen 1.2m in diameter and 1.0m in height, is capable of simulating four types of boundary conditions and consolidating soil specimens at various stress paths, including K_0 consolidation, by controlling σ_v with the piston plate and that of σ_h with the flexible double cylindrical wall.

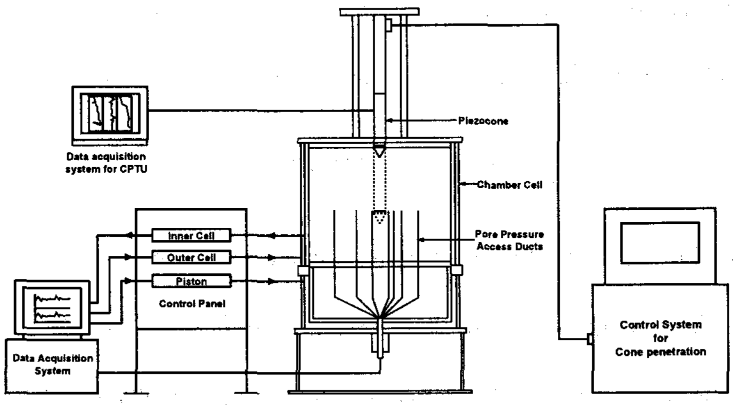


Figure 1. Korea Univ. Calibration Chamber System

3.2 Geotechnical Characteristics of Specimen

The specimen, which requires minimal consolidation time and maintains the mechanical properties of the cohesive soil, was developed specifically for this study and is referred to as KU-50. KU-50 is composed of 50% kaolinite and 50% Joomoonjin sand by weight, and its engineering properties are summarized in Table 1. The coefficients of consolidation in the vertical and horizontal directions were obtained from the oedometer tests on samples trimmed from the large specimen in the calibration chamber. The coefficients of consolidation were determined by the log t method and the values given in Table 1 are the average ones.

Table 1. Properties of KU-50 specimen

Property	Value
LL	33.5
PL	14.6
G_s	2.62
c_v	1.16×10^{-03} cm^2/sec
c_h	1.34×10^{-03} cm^2/sec

The undrained shear strength and the shear modulus are estimated by using CK_0UC tests, which were performed at various OCRs. The undrained response to shear in triaxial compression is shown in Figure 2 at each OCR, Table 2 summarizes the conditions and results of CK_0UC tests on the test specimens. It is observed that the NC specimen failed at a small deformation, while the deformations of the OC specimens at failure increased with increasing OCR. The relationship between s_u/σ'_{vc} and OCR for the KU-50 specimen was established in accordance with the SHANSEP method, as shown in Eq. 2.

$$\frac{s_u}{\sigma'_{vc}} = 0.35(OCR)^{0.84} \qquad (2)$$

Table 2. Conditions and results of CK_0UC tests

OCR	1	5	10	20
K_0	0.5	1.1	1.6	2.2
σ'_v (kPa)	200	40	20	10
σ'_h (kPa)	100	44	32	22
s_u (kPa)	70	54	48	43
G_{50} (kPa)	40000	4358	2290	2000
G_f (kPa)	40000	1200	640	410
ε_f(%)	0.05	3.0	5.0	7.0

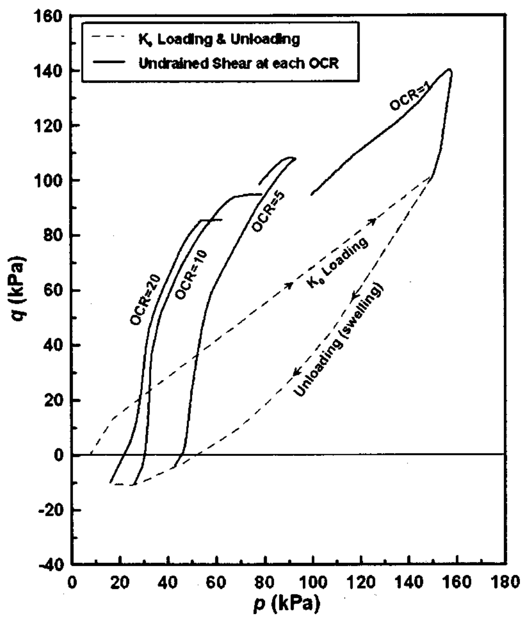


Figure 2. Stress path for KU-50

3.3 Piezocone Penetration Tests in Calibration Chamber

50% clay and 50% sand were mechanically blended at water content of twice the liquid limit to make KU-50 slurry. The slurry was carefully poured into a consolidometer and was loaded by means of a hydraulic actuator on the top plate. The consolidation pressure was increased from 10kPa to 160kPa with a load increment ratio of 1.0 every 24 hours and, then, the pressure of 160kPa was maintained through the rest of the slurry consolidation period. After the slurry consolidation, the specimen was reconsolidated following K_0 stress state in the calibration chamber and, in the final stage of consolidation, a vertical stress of 400kPa and horizontal stress of 300kPa were applied with a backpressure of 200kPa.

After completing the reconsolidation of the specimen in the calibration chamber, the piezocone was installed at the cone adaptor on the top lid. After the penetration and dissipation tests were conducted on NC clays, the specimen was unloaded to a specific OCR by following the stress paths used for the SHANSEP technique and then the tests were repeated. The relative distance between each penetration was set to be more than 15 times the cone radius, considering the radius of the plastic zone induced by penetration. All of the penetration tests were conducted with the u_2 type standard piezocone ($10cm^2$

projected cone area and 60° cone apex angle) with a penetration rate of 2cm/sec. The piezometers were installed around the planned penetration paths in the specimen through the chamber base plate, as shown in Figure 3, in order to measure the spatial distribution of the induced excess pore pressure.,

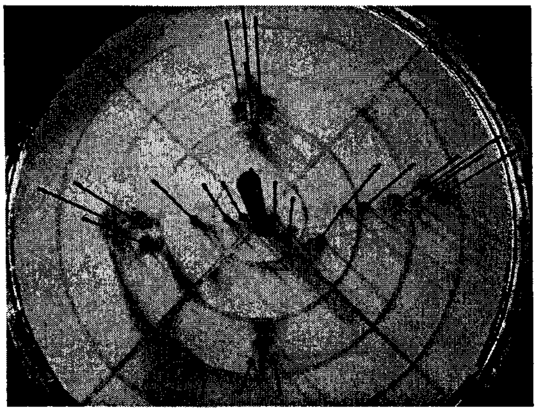


Figure 3. Piezometers installed on the base plate

4. THEORETICAL APPROACH

4.1 Zones of Influence due to Piezocone Penetration

The spatial distributions of each component of excess porewater pressure due to piezocone penetration in overconsolidated cohesive soil are assumed as shown in Figure 4. A logarithmic distribution is assumed to represent the initial excess porewater pressure induced by the octahedral normal stress (Δu_{oct}) in the shear and plastic zones, as suggested by the cavity expansion theory. The initial excess porewater pressure induced in the shear zone by the octahedral shear stress (Δu_{shear}) is assumed to vary linearly in the shear zone.

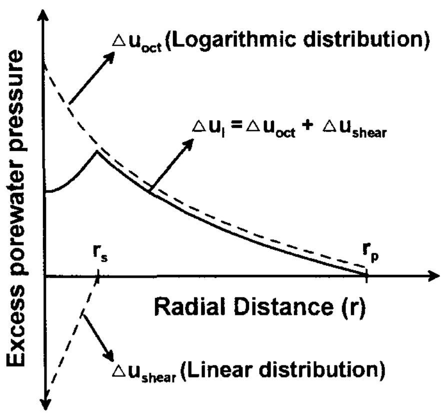


Figure 4. Distribution of each components of each Δu

Theoretical magnitudes of the shear and plastic zones are evaluated using cylindrical cavity expansion theory with an adequate rigidity index:

$$r_p = r_o\left(\frac{G_{50}}{s_u}\right)^{0.5} = r_o(I_r)^{0.5} \tag{3}$$

$$r_s = r_o\left(\frac{G_f}{s_u}\right)^{0.5} \tag{4}$$

where r_p is the radius of the plastic zone, r_s is the radius of the shear zone, r_o is the radius of the cone, G_{50} is the tangent shear modulus at 50% peak shear stress, G_f is the shear modulus at failure, and I_r is the rigidity index.

Due to the large shear strain in the shear zone during cone penetration, the radius of the shear zone is represented with the shear modulus at peak stress. Since the soil in the shear zone reaches a critical state during the piezocone penetration, the anisotropic stress condition does not appear to play an influential role in the shear zone. Therefore, the larger penetration rate of the piezocone than the strain rate of the laboratory triaxial test is likely to cause a difference between the predicted and measured shear radii. The factor employed to correct the effect of the strain rate on the rigidity index (α_s) is used to predict the shear radius:

$$r_s = r_o\left(\alpha_s\frac{G_f}{s_u}\right)^{0.5} \tag{5}$$

Since it is not easy to determine α_s by theoretical methods, it is evaluated empirically from the results of the test conducted in the calibration chamber.

4.2 Initial Excess Porewater Pressure

The excess porewater pressure induced by the cone penetration consists of two components due to the changes in the octahedral normal stress and the octahedral shear stress.

$$\Delta u = \Delta u_{oct} + \Delta u_{shear} \tag{6}$$

Under the cone tip, the largest effect on the magnitude of the porewater pressure is created by the changes in the mean normal stress. However, along the shaft of the cone body, the shear stresses induce a significant portion of the excess pore pressure because the octahedral normal stresses acting on the cone tip experience stress relief.

The undrained shear strength, by definition, is expressed as follows:

$$s_u = \frac{1}{2}q = \frac{M}{2}p'_f \tag{7}$$

where M is the slope of the critical state line in the p'-q plane, and p'_f is the mean effective stress at failure. By adopting the modified Cam clay model for the undrained shear strength from triaxial compression tests on isotropically consolidated samples (Wroth 1984) and the relation between the overconsolidation ratios in terms of the mean effective stress and the vertical effective stress (Chang et al. 1999), the undrained shear strength obtained from the K_0-consolidated triaxial compression test (CK_0UC) can be defined as follows:

$$s_u = \frac{1}{2}Mp'_0\left(\frac{\alpha_R OCR}{2}\right)^{\Lambda} \tag{8}$$

where p'_0 is the initial mean effective stress, OCR is the overconsolidation ratio in terms of vertical effective stress, $\alpha_R=[9(1-K_{0nc})^2+M^2(1+2K_{0nc})^2]/M^2(1+2K_0)(1+2K_{0nc})$, $K_0=K_{0nc}OCR^{\sin\varphi'}$, $K_{0nc}=1-\sin\varphi'$, and Λ is the plastic volumetric strain ratio.

To account for the difference between the strain rates of the laboratory test and in-situ penetration, the cylindrical cavity strain rate defined by Cao et al. (2001) is adopted.

$$\dot{\varepsilon} = \frac{1}{r_0}\frac{dr}{dt} = \frac{1}{r_0}\dot{s} \tag{9}$$

where $\dot{\varepsilon}$ is the equivalent strain rate in the laboratory test, r_0 is the radius of the cone, and $\dot{s}$ is the piezocone penetration rate. Once the factor to correct the effect of the strain rate (α_ε) is determined by Equations 1 and 9, the undrained shear strength and the mean principle effective stress at failure can be expressed as follows:

$$s_u = \alpha_\varepsilon \frac{1}{2}Mp'_0\left(\frac{\alpha_R OCR}{2}\right)^{\Lambda} \tag{10}$$

$$p'_f = \alpha_\varepsilon p'_0\left(\frac{\alpha_R OCR}{2}\right)^{\Lambda} \tag{11}$$

Since the shear component of the excess porewater pressure can be expressed as the difference between the initial and final mean effective stresses in the Cambridge p'-q space (Wroth et al. 1979), the shear-induced piezocone excess porewater pressure can be given as follows:

$$\Delta u_{shear} = p'_o \left[1 - \alpha_\varepsilon \left(\frac{\alpha_R OCR}{2} \right)^\Lambda \right] \tag{12}$$

Based on the cylindrical cavity expansion theory and the modified Cam clay model extended to consider the effect of the strain rate and the anisotropic stress condition, the octahedral component of the excess porewater pressure is derived as follows:

$$\Delta u_{oct} = \alpha_\varepsilon \frac{1}{2} M p'_o \left(\frac{\alpha_R OCR}{2} \right)^\Lambda \ln(I_r) \tag{13}$$

Recent works (Baligh and Levadoux 1986; Jamiolkowski et al. 1985) showed that the values of the coefficient of consolidation evaluated with G_{50} are adequate for soils in an OC state, and the rigidity index defined by G_{50} is used for the evaluation of Δu_{oct} in this study. Since a significant amount of octahedral normal stress due to piezocone penetration occurs within the shear zone, the magnitude of Δu_{oct} is corrected with respect to the strain rate, as in the case of the shear radius. The final expression for Δu_{oct} is given in Eq 14.

$$\Delta u_{oct} = \alpha_\varepsilon \frac{1}{2} M p'_o \left(\frac{\alpha_R OCR}{2} \right)^\Lambda \ln\left(\alpha_s \frac{G_{50}}{s_u} \right) \tag{14}$$

5. RESULTS AND ANALYSIS

5.1 Spatial Distribution of Δu

The piezometer installed nearest to the piezocone was susceptible to be displaced in the radial direction during the piezocone penetration and it can be observed from Figure 5 that there was a recovery of the lateral deformation after the withdrawal of the piezocone. The small displacement of the piezometer in the radial direction is not expected to affect the measurement of the pore pressure as long as the piezometer moves together with the soil around the piezocone.

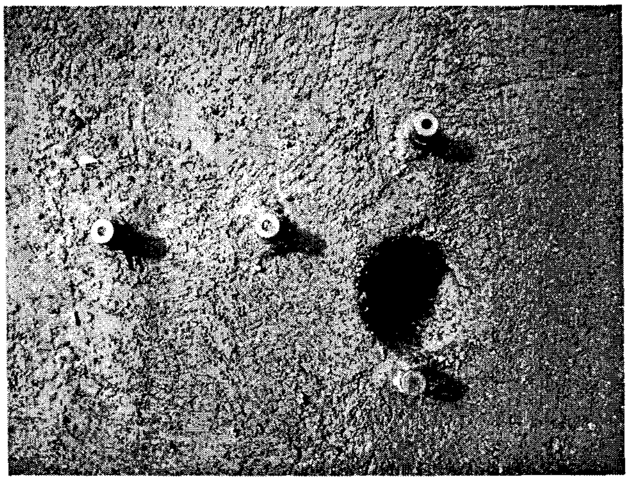


Figure 5. Piezometers and penetration hole after CPTU test

Figure 6 shows the normalized spatial distributions of the excess porewater pressure measured by the piezocone and piezometers in the NC and OC clays. It can be seen that the excess pore pressure due to the piezocone penetration in the NC clay decreases exponentially with increasing radial distance, while the excess pore pressure in the lightly OC clay shows a slight tendency to decrease, which can be explained by the fact that the excess pore pressure induced by the octahedral normal stress is larger than that induced by the octahedral shear stress. It is also observed that, for the moderately and heavily OC clays, the initial excess pore pressure increases from the piezocone porewater pressure to the maximum value and then decreases to the minimum value as the distance from the cone surface increases. The observed shapes of the spatial distributions of Δu that are observed can be explained by the different responses of the excess porewater pressure to the shear deformation caused by the piezocone penetration. It appears that the shear strain inside the shear zone is large enough to cause the dilation of the moderately or heavily OC soil, which, in turn, induces a negative Δu_{shear}. Since these dilatory trends increase as the OCR value increases, it is natural for the piezocone porewater pressure of OC clay to be smaller than that of NC clay.

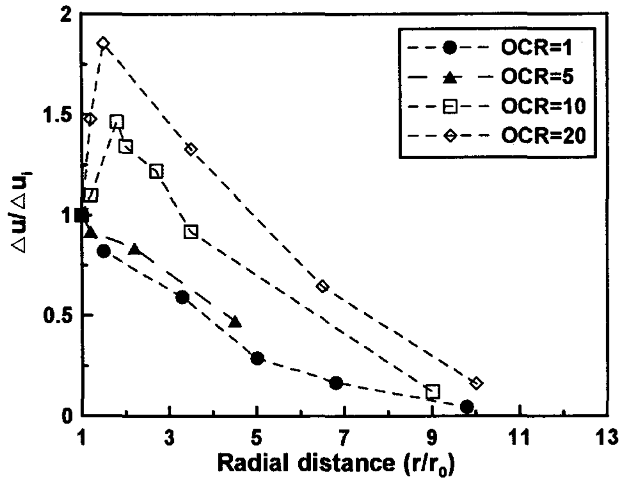


Figure 6. Spatial distributions of excess porewater pressure at each OCR

5.2 Evaluation of the Zones of Influence

From the spatial distributions of the porewater pressure measured in the calibration chamber, the probable sizes of the zones of influence can be evaluated for specimens with different OCR values. As mentioned above, the boundary between the shear and plastic zones is defined as the radius where the peak excess porewater pressure is generated, while the outer boundary of the plastic zone is defined as the radius where the excess porewater pressure converges to zero. In general, the plastic zone behind the cone tip was estimated by the cylindrical cavity theory under undrained conditions and the shape of the shear zone was assumed to be a small annulus (Burns and Mayne 1998). To investigate the difference between the predicted and measured zones of influence, the radius of each zone was theoretically predicted by the cylindrical cavity expansion theory with Eqs 3 and 4.

The size of the shear zone was evaluated by comparing the measured porewater pressures with the predicted distribution based on a linear increase of Δu_{shear} and a logarithmic decrease of Δu_{oct} within the shear zone. Though no distinctive peak was observed from the measured excess porewater pressure for the lightly OC clay (OCR=5), the radius of the shear zone is assumed to be $2.2r_o$ from the visual inspection of the distribution curve. The sizes of the shear zone at OCR=10 and OCR=20 are evaluated as $1.8r_0$ and $1.5r_0$, respectively. For the NC clay, the shear zone cannot be estimated, because the magnitude of the porewater pressure decreases monotonically from the cone location. From the results obtained herein, it was found that the radius of the shear zone decreases as the OCR increases. This is consistent with the results of the numerical analysis performed by Abu-Farsakh et al. (1998).

The plot to compare the predicted and measured sizes of the shear zone is shown in Figure 7. It can be seen that the radius predicted by the cylindrical cavity expansion theory is about two times larger than the measured one. Both results show a similar tendency of the shear radius to decrease with increasing OCR. The difference between the predicted and measured shear radii may be explained by the penetration rate of the piezocone being larger than the strain rate in the laboratory triaxial test. Therefore, in order to predict the shear radius accurately, the effect of the strain rate on the rigidity index has to be taken into consideration by using the correction factor, α_s, in Eq 5. From the data shown in Figure 7, the correction factor for the rigidity index is found to be in the range of 0.23~0.25 and, in this study, a value of 0.25 is used for the prediction of the shear zone.

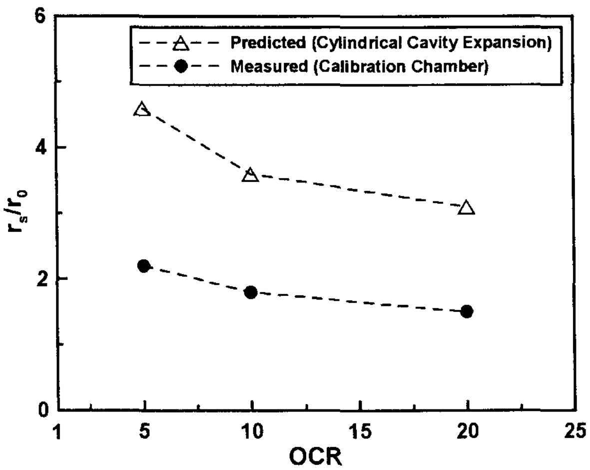


Figure 7. Variation of shear radius with OCR

The radius of the plastic zone was estimated from the regression analysis of the porewater pressures measured by the piezometers in the calibration chamber, assuming the logarithmic distribution of Δu_{oct} in the plastic zone. From the test results shown in Figure 6, it can be observed that the radius of the plastic zone is almost constant, regardless of the OCR value, and is in the range of $10.7\sim13.0r_o$. For the clay with OCR=5, because the farthest distance from the piezocone to the piezometer is $4.5r_0$ and there are only two probable data points within the plastic zone, the radius of the plastic zone is roughly estimated to be $11.4r_0$. The above observation that there is no specific trend in the variation of the size of the plastic zone with the OCR does not agree with the results of previous studies, which showed an increase in the size of the plastic zone with increasing OCR.

Figure 8 shows the variation of the radius of the plastic zone with the OCR. It can be seen that the plastic radius predicted by the cavity expansion theory decreases with increasing OCR, while the measured plastic radius is almost constant, regardless of the OCR. The plastic radii at OCR=10 and OCR=20 are underpredicted by about 34%~75%, while the predicted size at OCR=1 is about 2.2 times larger than the measured one.

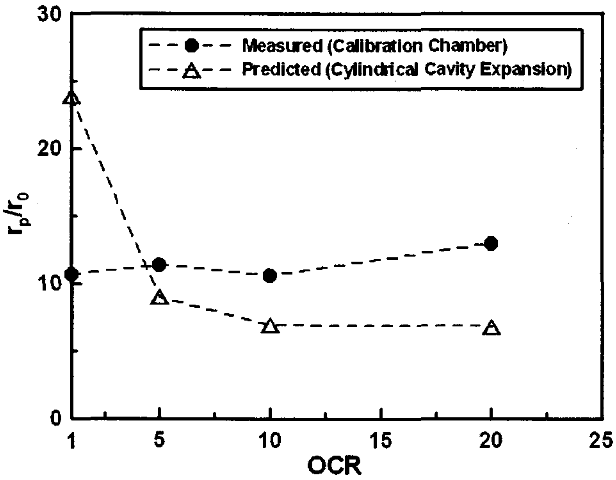


Figure 8. Variation of plastic radius with OCR

5.3 Initial Excess Porewater Pressure at Piezocone

Figure 9 shows a comparison of the measured piezocone porewater pressure and the theoretical value predicted by the equations derived in this study, in order to examine the effects of the initial stress condition and strain rate. It can be seen that when the effect of the strain rate is taken into account the piezocone pore pressure is under-predicted, whereas when the anisotropic stress condition is taken into account the pore pressure is overpredicted. The observation that the porewater pressures predicted while ignoring the anisotropic stress condition and strain rate agree quite well with the measured ones can be explained by the mutually contradictory effects of these two factors on the porewater pressure. In general, the predicted values which take into account both the strain rate and the anisotropic condition of the initial stress show the closest matches to the results of laboratory tests on OC clays.

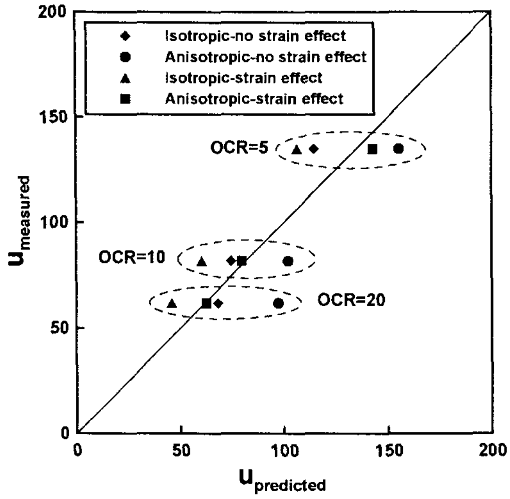


Figure 9. Effects of anisotropic stress state and strain rate on pore pressure

Figure 10 shows a comparison of the excess porewater pressure at the piezocone location measured in the calibration chamber with the values predicted in this study and by the methods of Burns and Mayne (1998) and Chang et al. (2001). It can be seen that the piezocone pore pressure predicted in this study is close to the results for OC clays measured in the chamber. The prediction by Burns and Mayne (1998) overestimates the porewater pressure by about 100% and this difference may be explained by the lack of consideration of the anisotropic stress condition and the use of a different shear modulus. Also, the value predicted by Chang et al. (2001) is almost constant, regardless of the OCR.

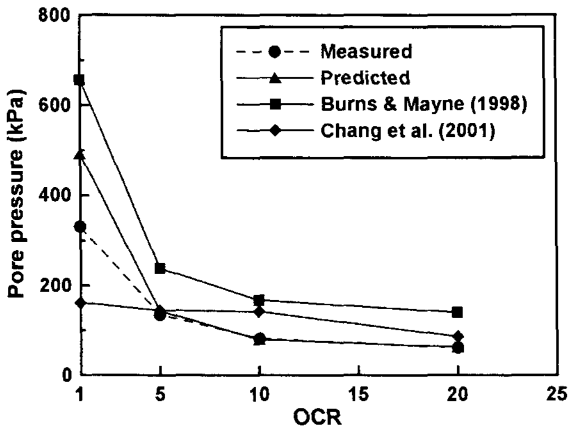


Figure 10. Pore pressure predicted by various methods

5.4 Verification of Initial Distribution of Porewater Pressure

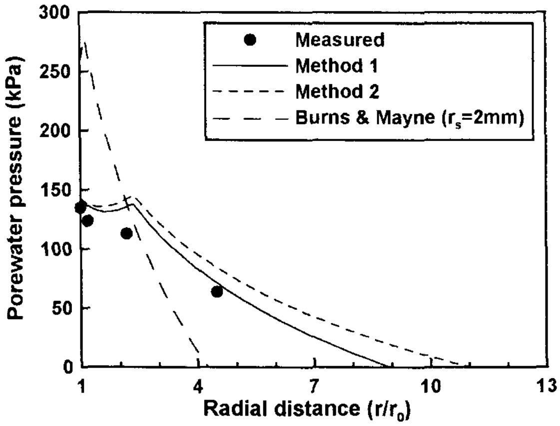
In order to verify the appropriateness of the semi-empirical method proposed in this study, the spatial distributions of the initial excess porewater pressure due to the piezocone penetration evaluated by several methods shown in Table 3 are compared with the results obtained in the calibration chamber tests.

Table 3. Comparison of the prediction methods

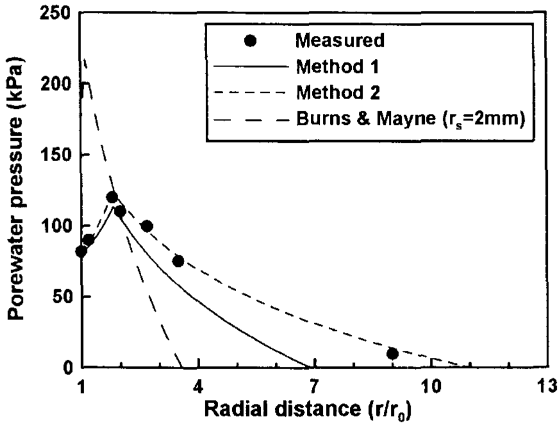
Reference	Size of influence zone	Initial porewater pressure
Burns & Mayne (1998)	r_s : 2mm r_p : spherical cavity	$\Delta u_{shear} = \sigma'_{vo}[1-(\frac{OCR}{2})^{\Lambda}]$ $\Delta u_{oct} = \frac{4}{3}\sigma'_{vo}\frac{M}{2}(\frac{OCR}{2})^{\Lambda}]\ln(\frac{G_{50}}{s_u})$
Method 1	r_s : $r_o(0.25\times\frac{G_f}{s_u})^{0.5}$ r_p : cylindrical cavity	$\Delta u_{shear} = p'_o[1-\alpha_\varepsilon\left(\frac{\alpha_R OCR}{2}\right)^{\Lambda}]$
Method 2	r_s : $r_o(0.25\times\frac{G_f}{s_u})^{0.5}$ r_p : $11.0r_0$	$\Delta u_{oct} = \alpha_\varepsilon\frac{1}{2}Mp'_o\left(\frac{\alpha_R OCR}{2}\right)^{\Lambda}\ln(0.25\times\frac{G_{50}}{s_u})$

Methods 1 and 2 predict the distribution of the porewater pressure based on the piezocone porewater pressure evaluated by the cavity expansion theory and modified Cam clay model, both of which take into consideration the effects of the strain rate and anisotropic stress condition. The correction factor (α_ε) determined was 1.56 and the correlation factor between the OCR and R (α_R) was 0.87 for OCR=5, 0.66 for OCR=10 and 0.52 for OCR=20. A constant value of 0.25 was used as the correction factor for the effect of the strain rate on the rigidity index (α_s). The plastic radius was determined by the cylindrical cavity expansion theory for method 1 and by assigning a constant value of 11 r_0 for method 2. For the purpose of comparison, the distribution predicted by the method of Burns and Mayne (1998) is also presented.

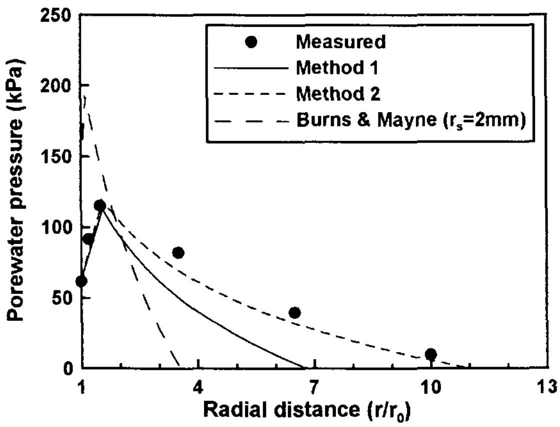
Figure 11 shows a comparison of the initial distribution of the excess porewater pressure evaluated by the different prediction methods with the results obtained in the calibration chamber. It can be seen that the proposed method with a constant plastic radius provides the best matches for all OCR values. The predictions made by Burns and Mayne (1998) show quite different distributions of the porewater pressure, because of the smaller size of the shear and plastic zones and the difference in the magnitude of the piezocone porewater pressure. From the observation of these figures, it can be concluded that the method proposed in this paper provides an excellent prediction of the excess porewater pressure distribution around the piezocone.



(a) OCR=5



(b) OCR=10



(c) OCR=20

Figure 11. Distribution of excess porewater pressure around cone at each OCR

6. CONCLUSIONS

This paper presented an analysis of the spatial distribution of excess porewater pressure induced by the piezocone penetration into overconsolidated clay in a large calibration chamber, from which the sizes of the shear and plastic zones formed around the cone were evaluated. For the prediction of the piezocone porewater pressure, expressions were developed for the octahedral normal and shear components of the excess porewater pressure, which take into consideration the effects of the strain rate and the anisotropic stress condition. The verification of the proposed method was accomplished by comparing the predicted distribution of the excess porewater pressure with the experimental results. The conclusions drawn from the present study can be summarized as follows:

1. For moderately and heavily OC clays, an increase in the excess porewater pressure to a peak value within the shear zone was observed, followed by a logarithmic decrease to zero porewater pressure with increasing distance from the piezocone surface. This clearly shows the formation of the shear zone around the piezocone penetrating into the soils with OCR values of 10 and 20.
2. It was found from the measured spatial distribution of the porewater pressure induced by the piezocone penetration that the size of the shear zone ranges from 1.5 to 2.2 times the piezocone radius and decreases with increasing OCR. The size of the shear zone predicted theoretically by the cylindrical cavity expansion theory with shear modulus G_f is about two times larger than the measured value, while both show a similar tendency for the shear radius to decrease with increasing OCR. The difference may be due to the effect of the strain rate, and the use of a correction factor α_s of 0.25 is suggested for the prediction of the shear zone by the cylindrical cavity expansion theory.
3. It was observed from the results of the tests conducted in the calibration chamber that the plastic region radius is almost constant, regardless of the OCR, and its average radius is about 11 r_0. This observation is quite different from the results of previous studies, in which it was suggested that the size of the plastic zone decreased with increasing OCR.
4. The initial pore pressure at the piezocone location is predicted well by summing the octahedral normal and octahedral shear components of the excess porewater pressure based on the cavity

expansion theory and modified Cam clay model using correction factors for the strain rate and stress anisotropy. Though the prediction, which does not take into consideration the effects of the strain rate and stress anisotropy, presents a good match with the measured porewater pressures, due to their mutually contradictory effects on the porewater pressure, it is more logical to consider both effects.

5. The method proposed in this study, based on a linearly increasing value of Δu_{shear} in the shear zone and on a logarithmically decreasing value of Δu_{oct}, offers a good prediction of the spatial distribution of the porewater pressure around the piezocone when using a constant plastic radius and a shear radius which decreases with increasing OCR.

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