Study on Cone Penetration Rate and Anisotropy in Cohesive Soils
점성토에 있어서 지반의 비등방성을 고려한 콘 관입속도에 관한 연구

Dae-Kyu Kim, 김대규[1], Woo-Jin Lee, 이우진[2]

[1] Senior Researcher, Research Center for Disaster Prevention Science and Technology, Korea University, 고려대학교 부설 방재과학기술연구센터 선임연구원
[2] Associate Professor, Dept. of Civil Engineering, Korea University 고려대학교 토목환경공학과 부교수

개 요 : 본 연구에서는 비등방성 응력조건 하에서 콘 관입속도가 콘 관입시험 결과에 미치는 영향을 연구하기 위하여 유한요소해석 및 Calibration Chamber를 이용한 Miniature Piezocone의 관입시험이 수행되었으며 그 결과를 비교 분석하였다. 비등방성을 고려하기 위하여 Anisotropic Soil Model이 유한요소해석에 이용되었으며 LSU/CALCHAS(Louisiana State University Calibration Chamber System)가 Miniature Piezocone의 관입시험에 이용되었다. 콘 관입속도의 영향이외에도 OCR 및 필터위치의 영향을 고찰하였다.

KeyWords : Penetration Rate, LSU/CALCHAS, Piezocone, Calibration Chamber, Anisotropy, bounding surface model

1. INTRODUCTION

Interpretations of the data from piezocone penetration test are often complex as they are influenced by a number of variables related to the design of the cone, testing procedure, and soil characteristics (Tumay, et al., 1998; Voyiadjis, et al., 1994; Kurup, et al., 1994). The rate of penetration and soil anisotropy are two important influencing factors.

The standard rate of penetration test is 2cm/sec. The cone resistance tends to decrease for the penetration rate less than 2cm/sec (Acar, 1981; Campanella and Robertson, 1981). The penetration rate has also an influence on excess pore water pressure and sleeve friction (Roy, et al., 1982; Campanella and Robertson, 1981). If the mechanism of piezocone penetration needs to be theoretically analyzed, the use of viscoplasticity would be recommended since elastoplasticity alone can not account for time dependent behavior such as strain rate effect.

Soil anisotropy is one of the influencing factors related to soil characteristics. Field and laboratory investigations have now established that anisotropy significantly influences the stress-strain behavior of soils (Banerjee, et al., 1984; Wroth and Houlsby, 1985).

As stated above, since many factors influence the piezocone penetration test, the effects of the factors should be considered for an accurate interpretation of piezocone penetration mechanism, and an experimental study needs to be conducted to prove the interpretation method using a well-calibrated equipment.

In this research, the influence of penetration rate, OCR, and filter element location on the results of piezocone penetration test has been investigated through both a finite element method, which adopted an anisotropic elastoplasic-viscoplastic soil model, and laboratory model test using a miniature piezocone and LSU/CALCHAS (Louisiana State University Calibration Chamber System).

In the following sections, the finite element analysis and the experiment are briefly described, and the results of the finite element analyses are compared with the experimental results.

2. Finite Element Analysis

In this research, the anisotropic elastoplastic-viscoplastic bounding surface model (Al-Shamrani and Sture, 1994) was used to incorporate anisotropy and viscoplastic effects. An important feature of bounding surface model is the plastic deformations can occur for the stress states either within or on the bounding surface (contrary to the classical plasticity). it is also 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. Equation (1) shows the constitutive relation of the model.

$$\dot{\sigma}_{ij} = E^{ep}_{ijkl}\,\dot{\varepsilon}_{kl} - \varphi_{ij} \qquad (1)$$

where E^{ep}_{ijkl} is elastoplastic stiffness matrix and φ_{ij} is viscoplastic contribution.

A finite element formulation for piezocone penetration was performed considering the viscoplastic contribution to implement the model. The formulation was based on virtual work equation. Equation (2) shows the final governing equation in matrix form.

$$\begin{bmatrix} {}_n\mathbf{K} & -{}_n\mathbf{\Omega} \\ -{}_n\mathbf{\Omega}^T & -\delta t\,{}_n\Psi \end{bmatrix} \begin{Bmatrix} \Delta U \\ \Delta W \end{Bmatrix} = \begin{Bmatrix} {}_n\Phi \\ {}_n\Pi \end{Bmatrix} \qquad (2)$$

where ΔU is the incremental nodal displacement and ΔW is the incremental nodal excess pore water pressure.

The piezocone penetration was treated as an axi-symmetric boundary problem (Kiousis, et al., 1988; Sandven, 1990; Teh and Houlsby, 1991; Voyiadjis and Abu-Farsakh, 1997), and the piezocone was assumed to be infinitely stiff and no tensile stresses were allowed to develop along the centerline boundaries. Since the soil around the piezocone undergoes substantial displacements during penetration, a large deformation and finite strain formulation was used in this analysis. To avoid the tremendous computational errors in the transient state due to large rotations of the elements involved, the piezocone was assumed to be initially pre-bored to a certain depth with the initial stresses remaining unchanged (Devorst and Vermeer, 1984; Voyiadjis and Abu-Farsakh, 1997).

The continuous penetration of piezocone was simulated by applying an incremental vertical displacement of the piezocone boundary. The vertical displacement could be applied at various rates but 0.3 cm/sec and 0.6 cm/sec were applied which were the same rates at the piezocone penetration tests conducted using LSU/CALCHAS.

3. Piezocone Penetration Test

Since details on the piezocone penetration test have been described in Kim (2000), only summary is presented here. The piezocone penetration test using LSU/CALCHAS can be found in Kurup (1993) and Kim (1999).

Ten piezocone penetration tests were conducted using LSU/CALCHAS (Louisiana State University Calibration Chamber System), the Slurry Consolidometer (Kurup, et al., 1994), and the miniature piezocone under Ko condition, at the penetration rates 0.3 cm/sec and 0.6 cm/sec, and for normally consolidated specimen and heavily overconsolidated (OCR=10) specimen. A mixture of 33% kaolin and 67% fine sand by dry weight was used as a soil specimen.

The procedure of the piezocone penetration test is as the following. First, the dry soil sample is mixed with water and the soil slurry is placed in the consolidometer. After the slurry consolidation in the consolidometer, the soil specimen is moved into the calibration chamber. The piezocone penetration test is conducted after reconsolidation in the calibration chamber.

The miniature piezocone fabricated by Fugro B.V., the Netherlands, on loan to Professor Mehmet T. Tumay, was used for the tests. It has a projected cone area of 100 mm^2, a cone apex angle of 60, a friction sleeve area of 1526 mm^2, and a slope sensor. The miniature piezocone has two alternatives for the filter location. The filter can be located at the very cone tip (U1 configuration, figure 1) or at 1 mm above the base of the cone (U2 configuration, figure 2).

Table 1 shows the stress conditions for reconsolidation and piezocone penetration test. Figure 3 and figure 4 show the LSU/CALCHAS.

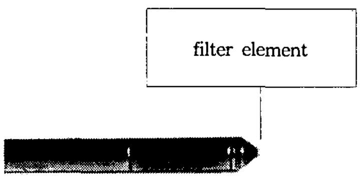

Figure 1 U1 configuration

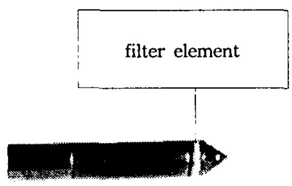

Figure 2 U2 configuration

Table 1 Miniature piezocone penetration test program

Penetration Test no.	Filter location	σv (kPa)	σh (kPa)	Ko	OCR	Penetration Rate (cm/sec)
1	u1	262.01	110.04	0.42	1	0.3
2	u1	262.01	110.04	0.42	1	0.3
3	u2	262.01	110.04	0.42	1	0.3
4	u2	262.01	110.04	0.42	1	0.3
5	u1	262.01	110.04	0.42	1	0.6
6	u1	262.01	110.04	0.42	1	0.6
7	u2	262.01	110.04	0.42	1	0.6
8	u2	262.01	110.04	0.42	1	0.6
9	u2	26.20	41.40	1.58	10	0.6
10	u1	26.20	41.40	1.58	10	0.6

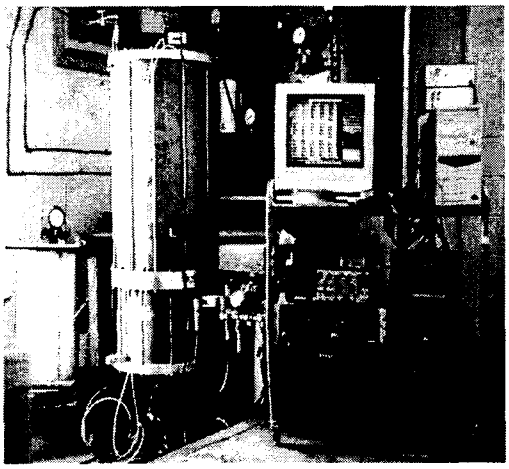

Figure 3 LSU/CALCHAS

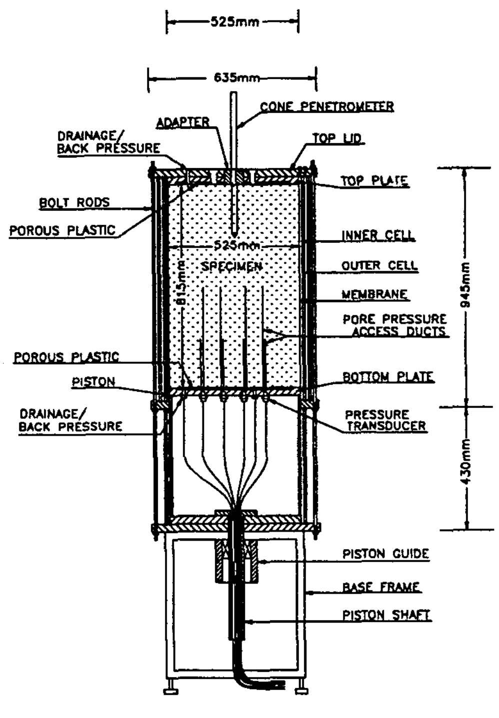

Figure 4 Schematic of flexible double wall calibration chamber (Kurup, 1993)

4. Results of Finite Element Analysis and Experiment

In this section, the results (cone resistance and excess pore water pressure) of the finite element analyses and the experiments of the piezocone penetration tests are presented and compared with each other. As shown in the miniature piezocone penetration test program (table 1), the penetration test no.2, no.4, no.6, and no.8 are the replications of the penetration test no.1, no3, no.5, and no.7, respectively. The replications have been conducted to confirm the reliability of the test results. The maximum difference between the results of the tests and the results of the replications were less than 9 %, so only the averages are presented.

4.1 Cone Resistance

The cone resistance was expressed as the corrected cone resistance, q_T, and back pressure, u_o. The corrected cone resistance was obtained from the measured cone resistance and the pore water pressure measured behind the cone tip (Tumay and Acar, 1985; Kurup, 1993). The area ratio of the miniature piezocone used in this research was 0.62. Figure 5 through figure 7 show the results of finite element analyses together with experimental results. In the finite element analyses, cone resistances of U1 and U2 configurations are not differentiable. Pore water pressures, on the other hand, are differentiable and they are presented in the following section.

As shown in figure 5 to figure 7, in all cases, the steady values from finite element analyses were very close to those obtained experimentally, and it has been observed that cone resistance increased with the increase in penetration rate but decreased with the increase of OCR as described in Kim (2000).

The cone resistance computed numerically reached the steady state conditions at the depth of 30 mm, that is shallower than that of experimental data. This disagreement is due to the peak regions, that occurred before the steady state, of the experimental data. These peak regions can be thought as the influence of the thin sand layer at the top of the specimen and occur to initiate the penetrations. Without the peak regions, the results of finite element analyses would have been much closer to the experimental data. Therefore, the simulation of the peak region needs further future research. However, the finite element analysis used in this research still shows better results, both for the cone resistance value at steady state and for the corresponding depth, than the previous numerical analyses found in literature. The use of the anisotropic elastoplastic-viscoplastic soil model is the reason for this better compliance.

4.2 Excess Pore Water Pressure

As shown in figure 8 to 10, excess pore water pressure increased with the increase in penetration rate but decreased with the increase of OCR, and it has been also observed that the excess pore water pressure of U1 type was larger than that of U2 type as described in Kim (2000). The steady values of excess pore water

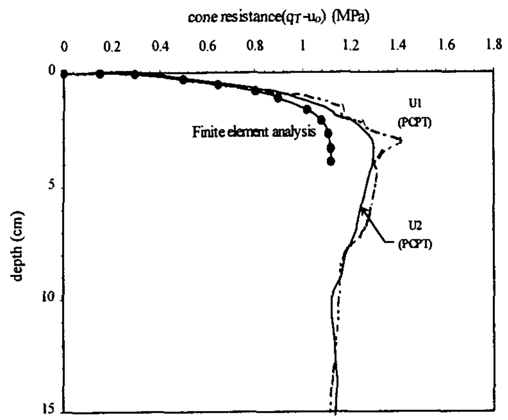

Figure 5 Cone resistance of NC specimen at 0.3 cm/sec

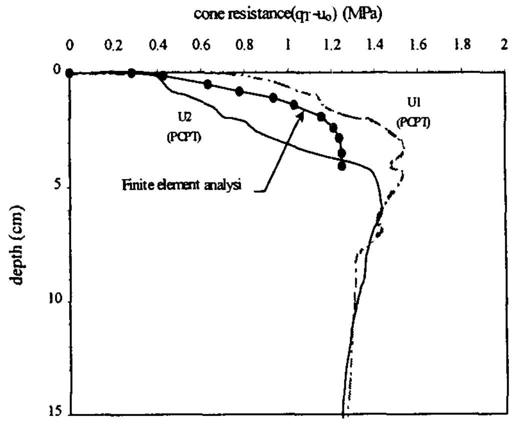

Figure 6 Cone resistance of NC specimen at 0.6 cm/sec

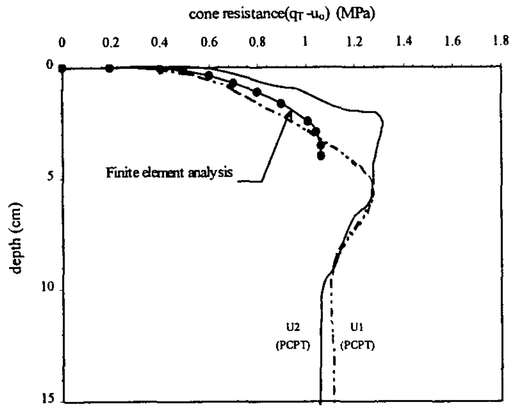

Figure 7 Cone resistance of OCR=10 specimen at 0.6 cm/sec

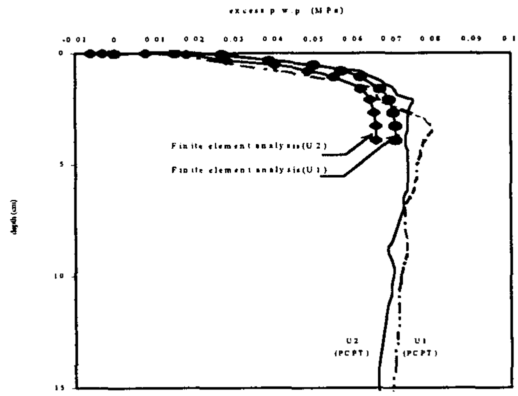

Figure 8 Excess p.w.p. of NC specimen at 0.3 cm/sec

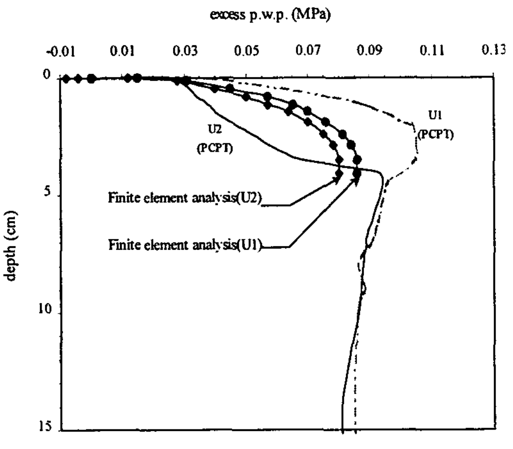

Figure 9 Excess p.w.p. of NC specimen at 0.6 cm/sec

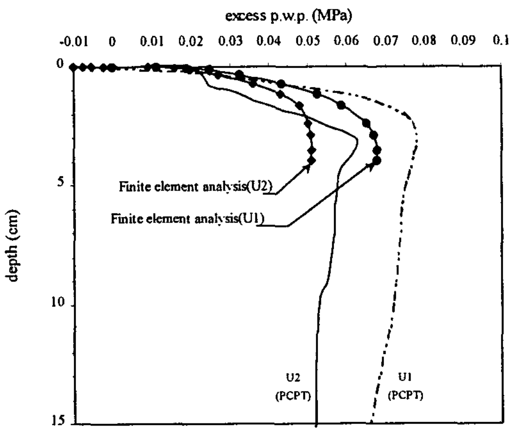

Figure 10 Excess p.w.p. of OCR=10 specimen at 0.6 cm/sec

pressures computed numerically were quite close to those obtained experimentally. The excess pore water pressures obtained from finite element analyses reached the steady state conditions at the depth of 30 mm, that is shallower than that of experimental data. This disagreement is due to the peak regions of the experimental results like in the cone resistance profiles.

It is interesting to note that negative pore water pressures were likely to develop above the cone base at the early stage of the penetration. It is due to the soil-piezocone separation near the cone base.

5. Conclusions

In this research, the finite element analysis and experiment of piezocone penetration were conducted and the results were compared with each other to investigate the effect of penetration rate, OCR, and the location of filter element on cone resistance and excess pore water pressure. The following conclusions could be made.

1. The steady values of cone resistance and excess pore water pressure from the finite element analyses were very close to the values obtained experimentally. Incorporation of the anisotropic elastoplastic-viscoplastic soil model provided this improvement.
2. The cone resistance and the excess pore water pressure computed numerically reached the steady state conditions at the depth of 30 mm, that was shallower than that of experimental results. This disagreement is due to the boundary induced peak regions, which occurred before the steady state, of the experimental results.
3. It was observed that negative pore water pressures from the finite element analyses were likely to develop above the cone base at early stages of penetration. It may be due to the soil-piezocone separation near the cone base in finite element analyses.
4. The cone resistance and excess pore water pressure increased with the increase in penetration rate, but decreased with the increase of OCR.
5. The excess pore water pressure measured at the cone tip (U1 configuration) was greater than that measured above the cone base (U2 configuration), unlike the cone resistance.

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