Numerical Simulation of Piezocone Dissipation Test in Dilating Soils
과압밀점토지반의 Piezocone 소산시험에 대한 수치해석기법

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개 요 : 피에조콘관입시험(PCPT)의 소산시험은 in-situ 상태의 압밀계수(c_v)를 추정하는 방법으로 널리 이용되어왔다. 본 연구에서는 spherical cavity expansion theory 및 axisymmetric uncoupled linear consolidation equation(Gupta & Davidson, 1986)을 이용하여 과압밀점토에서의 초기과잉간극수압의 분포 및 과잉간극수압의 시간에 대한 소산현상을 해석하는 수치해석방법을 제안하여 현장시험결과 및 실내시험결과와 비교 분석하였다. ADIS (alternating direction implicit scheme)를 이용한 FDM 해석을 실시한 결과와 현장시험의 소산곡선은 잘 부합되는 것으로 나타났으며 압밀계수도 실내실험 또는 피에조콘관입시험에 대한 추정방법으로 산출된 값과 비교적 일치하는 것으로 나타났다.

Key Words : cavity expansion theory, uncoupled linear consolidation equation, piezocone, coefficient of consolidation, excess pore pressure

1. Introduction

The cone penetration test (CPT/PCPT) is used throughout the world to determine the subsurface stratigraphy and is generally accepted as a valuable test for the in-situ investigation of many types of soil deposit. Its principal advantages over other investigation procedures are the relative rapidity of the test, the possibility of obtaining continuous specific character of strength with depth and the wide application of its result. Furthermore, in recent year, there has been an increasing trend to use the cone penetration test (PCPT) as an in-situ tool of choice for determine the consolidation and flow characteristics of cohesive soil.

The cone penetration test began as quite a simple test, but with the addition of the friction sleeve and the pore pressure measuring system, the applicability and usage of the cone penetration test has increased. The more the actual mechanics regarding the insertion of the cone are realized, the more accurate correlation may be made. In that reason many attempts have been made to theoretically model the mechanics involved during the time-dependent dissipation of excess pore pressure and the initial excess pore pressure distribution.

The prominent factor in the modeling of the dissipation test concerns the determination of the initial pore pressure distribution, with the spherical and cylindrical cavity expansion theory representing the theoretical methods most widely accepted. The cavity expansion theory utilizes the stress change and deformation caused by penetration of the cone into the ground in predicting the initial excess pore pressure distribution. Although the cavity expansion theory is most agreeable in the case of normally consolidated and slightly overconsolidated clays, it leaves much to be desired in the case of overconsolidated clays.

In this research, a numerical analysis method is presented to model the initial excess pore pressure distribution and the dissipation of excess pore pressure with time for dilating soils through the integration of the cavity expansion theory and an axisymmetric uncoupled linear consolidation equation.

2. Initial excess pore pressure distribution

2.1 Introduction

The excess pore water pressure measured by piezocone is a combination of two different stress, such that

$$\Delta u = \Delta u_{oct} + \Delta u_{shear} \qquad (1)$$

u_{oct} is the octahedral excess pore pressure and u_{shear} is shear-induced excess pore pressure
According to Campanella et al(1988), when saturated soils are subjected to an increase in octahedral stresses, positive pore pressures are generated. When subjected to only shear stresses, pore pressures generated can be either positive or negative depending on the contractive or dilative response of the soil to shear.

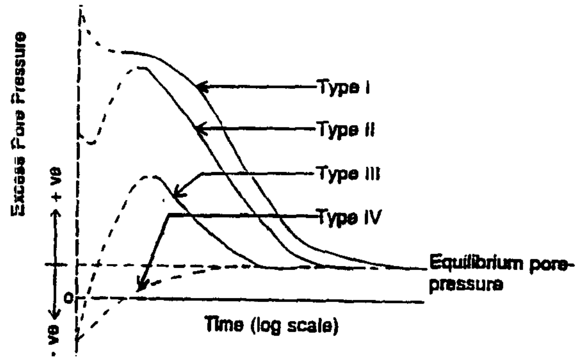


Figure 2.1 Initial Excess Pore Pressure Dissipation (Kurup & Tumay, 1995)

The initial excess pore pressure distribution due to piezocone penetration in clays, is an important factor affecting the interpretation of the coefficient of consolidation. In normally consolidated clay, methods using spherical cavity expansion theory and strain path are relatively good approximation of initial excess pore pressure distribution and dissipation analysis. In stiff heavily consolidated clays, the excess pore pressure above the base of the cone could increase initially due to redistribution around the tip (figure 2.1 TypeII and TypeIII). During the piezocone penetration, the excess pore pressures behind the tip could become negative, because of the high shear stresses and the heavily overconsolidated nature of the soils. Upon stopping penetration, these negative excess pore pressures are quickly swamped by inflow from the higher positive pore pressure zone in front of the tip and a peak pore pressure is reached which then dissipates with time back toward zero.

2.2 Cavity expansion theory

The cavity expansion theory is based on assumption of undrained soil response and the shear stresses acting on an element are zero. Figure 2.2 is the general form of expansion of cavity induced penetration. The equation of equilibrium in the radial direction is

$$\frac{\partial \sigma_r}{\partial r} + A\frac{\sigma_r - \sigma_\theta}{r} = 0 \qquad (2)$$

Where, A = 2 for spherical expansion, A = 1 for cylindrical expansion, and r is the distance to the center of cavity.

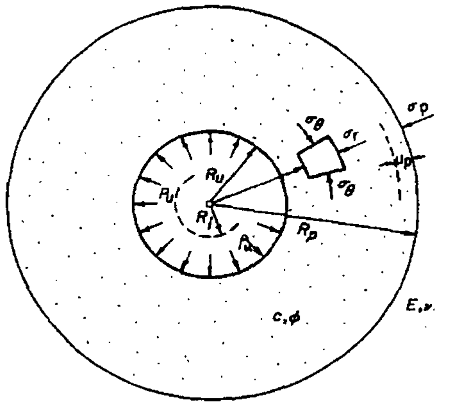


Figure 2.2 Expansion of cavity (Vesic, 1972)

Vesic(1972) considered the effects of volume change in the plastic region. He assumed that the soil in the plastic zone behaves as a compressible plastic solid, defined by Coulomb-Mohr shear strength parameters c and ϕ, as well as by an average volumetric strain Δ, which can be determined from known state of stress in the plastic zone and volume change-stress relationship. Beyond the plastic zone the soil is assumed to behave as a linearly deformable, isotropic solid defined by a modulus of deformation, E, and a Poissons ratio ν. It is further assumed that prior to the application of the load the entire soil mass has an isotropic effective stress q and that the body forces within the plastic zone are negligible when compared with existing and newly applied stresses.

Using above assumptions, Vesic(1972) developed the following expressions for excess pore pressures. For a spherical cavity,

$$\Delta u = \left[0.943\alpha_f + 4\ln\left(\frac{R_p}{r}\right)\right]c \quad \text{in the plastic zone} \qquad (3)$$

$$\Delta u = 0.943\alpha c\left(\frac{R_p}{r}\right)^3 \quad \text{in the outside of the plastic zone} \qquad (4)$$

The Henkel's pore pressure parameter at failure, α_f, in this equation is related to the Skemptons pressure parameter A_f by

$$\alpha_f = 0.707(3A_f - 1), \quad A_f = \frac{q}{c} + \frac{1-\sin\phi'}{2\sin\phi'}, \quad 0 < \alpha < \alpha f \qquad (5)$$

3. Piezocone dissipation analysis method (Gupta and Davidson, 1986)

Based on the cavity expansion theory, Gupta and Davidson (1986) suggested the following method for predicting the initial excess pore pressure distribution around a piezocone when it is stopped after penetration.

The method consists of matching the field piezocone dissipation curve with computer-generated dissipation plots. The initial excess pore pressure distribution was assumed using Vesic's cavity expansion theory (1972). The details are presented as following.

3.1 Initial excess pore pressure distribution in non-dilating soils

During steady penetration of the piezocone into a soil without dilatency effects, the penetration pore pressures are developed as shown in figure 3.1. When the piezocone is at point A, for example, the excess pore pressure around this point will be related to the measured penetration pore pressure, u_A, at point A (figure 3.1). using the logarithmic distribution given by equation (3), the initial excess pore pressure at any point B in the zone APQR is

$$\Delta u_B = \frac{(u_A - u_{0A})[0.943\alpha_f + 4\ln(\frac{R_p}{r_B})]}{[0.943\alpha_f + 4\ln(\frac{R_p}{r_A})]} \tag{6}$$

where u_{0A} is the hydrostatic pore pressure at point A before any effect of penetration of the piezocone.

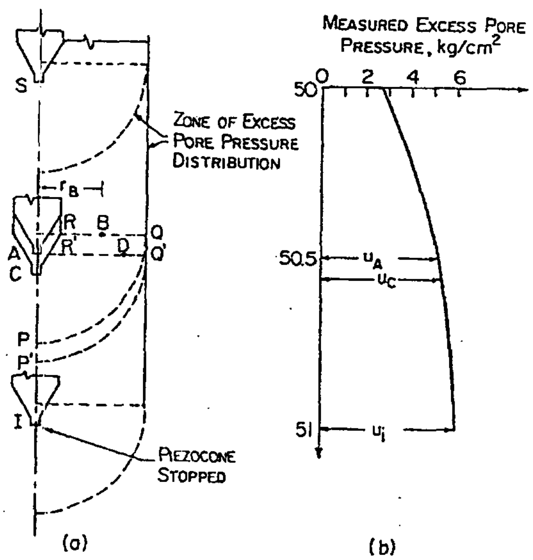


Figure 3.1 Schematics for Excess Pore Pressure Distribution (a) Successive Undrained Cavity Expansion, (b) A Typical Measured Pore Pressure versus Depth Curve (Gupta, 1983)

If the piezocone penetrates from A to C in time *t*, then the excess pore pressures calculated at points such as B, on the basis of the measured pore pressure at A, will dissipate. Dissipation depends upon the coefficient of consolidation, the pore pressure distribution around the point being considered, the time interval *t* and drainage boundaries. This dissipation must be taken into account for all points that lie above the mid-height of the cone at its present location.

3.2 Initial excess pore pressure distribution in dilating soil

Gupta (1983) were assumed that the ground surrounding the piezocone following penetration has been divided into too distinct zones. The inner zone around the piezocone experiences a tendency for volume expansion, due to the undrained shearing caused by insertion of the probe. Negative excess pore pressures therefore developed in this inner zone. The outer zone, which surrounds the inner zone, is subjected to isotropic elastic compression and develops positive pore pressure. Both the inner and outer zones were assumed to have spherical symmetry below the cone and cylindrical symmetry along the shaft. In the inner zone, the logarithmic distribution of negative excess pore pressure represented by equation (6) was assumed. In the outer zone, the distribution of positive excess pore pressure was assumed to follow a cubic curve, represented by the following equation.

$$u_{er} = u_{eR} \times (\frac{R}{r})^3 \tag{7}$$

where, u_{er}, u_{eR} = the positive excess pore pressure at radial distance r and R

R = the radius of the outer boundary of the inner zone.

3.3 Analysis of initial excess pore pressure dissipation

The corrected pore pressure distribution was used in a dissipation analysis based on the Terzaghi - Rendulic uncoupled consolidation theory.

$$c_v \frac{\partial^2 u_e}{\partial z^2} + c_h \frac{\partial^2 u_e}{\partial r^2} + \frac{c_h}{r}\frac{\partial u_e}{\partial r} = \frac{\partial u_e}{\partial t} \tag{8}$$

where, c_v, c_h = coefficient of the consolidation in vertical or horizontal direction

u_e = excess pore pressure

r = radial distance from the central axis of the cone

The alternating direction implicit schemes, which lead to a perturbation of the Crank-Nicolson equation, are locally second-order correct in space and time, are unconditionally stable, and each of the algebraic systems is tridiagonal. The method first evaluates the r derivative at n+1/2 and obtains a first approximation u_{n+1} at time n+1 from

$$\frac{1}{2}c_h\delta_r^2(u^*_{i,j,n+1} + u_{i,j,n}) + \frac{1}{2}\frac{c_h}{r}\delta_r(u^*_{i,j,n+1} + u_{i,j,n}) + c_v\delta_z^2 u_{i,j,n} = \frac{u^*_{i,j,n+1} - u_{i,j,n}}{\Delta t} \tag{9}$$

then moves the equation of the z derivative ahead by means of

$$\frac{1}{2}c_h\delta_r^2(u^*_{i,j,n+1} + u_{i,j,n}) + \frac{1}{2}c_v\delta_z^2(u_{i,j,n+1} + u_{i,j,n}) + \frac{1}{2}\frac{c_h}{r}\delta_r(u^*_{i,j,n+1} + u_{i,j,n}) = \frac{u_{i,j,n+1} - u_{i,j,n}}{\Delta t} \tag{10}$$

where is a central difference operator for the variables.

The solution of these equations is obtained by Thomas algorithm and is incorporated in program PIEZ. V. 1.

4. Suggestion of piezocone dissipation analysis in dilating soils

Based on the previous research results, a new method is recommended for predicting the initial excess pore pressure distribution around a piezocone in dilating soil when it is stopped after penetration.

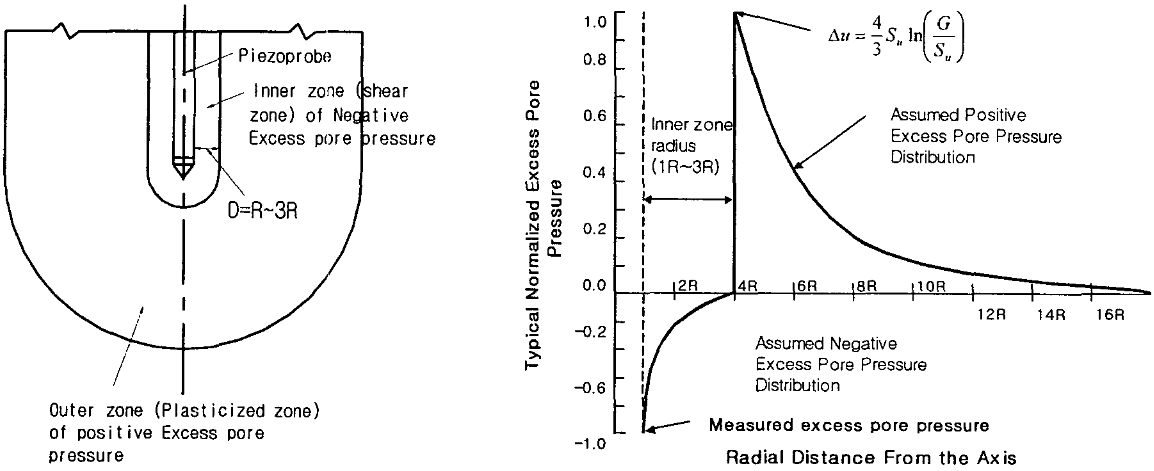
The following assumptions are made

(1) The inner zone(shear zone) radius were assumed from 1R to 3R.

(2) In the plasticized zone, only the octahedral normal-induced pore pressure developed and the maximum excess pore pressure at border between inner zone and outer zone, when piezocone stops penetration, is calculated using following equation.

$$\Delta u = \frac{4}{3} S_u \ln \frac{G}{S_u} \quad \text{spherical cavity (Torstensson, 1977)} \qquad (11)$$

(3) Gupta's (1983) general assumptions for non-dilating and dilating soils are valid.



(a) (b)

Figure 4.1 Assumed initial conditions (a) Inner zone and outer zone, (b)Excess pore pressure distribution in dilating soils.

5. Analysis of piezocone dissipation results in dilating soils

5.1. Laboratory and field test results (performed by Gupta, 1983)

Electrical piezocone sounding were performed at Deerhaven Power House Site. Undisturbed samples using a Swedish Fixed piston sampler were obtained from the depths of interest. Laboratory specimens from these undisturbed samples were used in one-dimensional consolidation tests and in undrained triaxial shear test. Atterberg limits were also determined.

Estimating soil properties for analysis piezocone dissipation test are in table 5.1.

Table 5.1 Laboratory and field test results from Deerhaven Power House site.

Depth (m)	S_u (kg/cm^2)	E (kg/cm^2)	m_v	A_f
3.81	0.89~1.14	294~342	0.01	-0.15
4.81	0.21	63	0.01	-0.15
5.81	0.66~0.83	198~247	0.18	-0.15
6.81	1.05~1.35	315~405	0.2	-0.15

5.2. Analysis of dissipation data using computer program named PIEZ. V. 1.

The predicted dissipation analysis results using computer program are shown in from figure 5.1 to 5.4. The excess pore pressure u_i indicates excess pore pressure at the tip of the piezocone where the porous element located and D is the inner zone radius. Several analyses were made with different values of D from 1R to 3R.

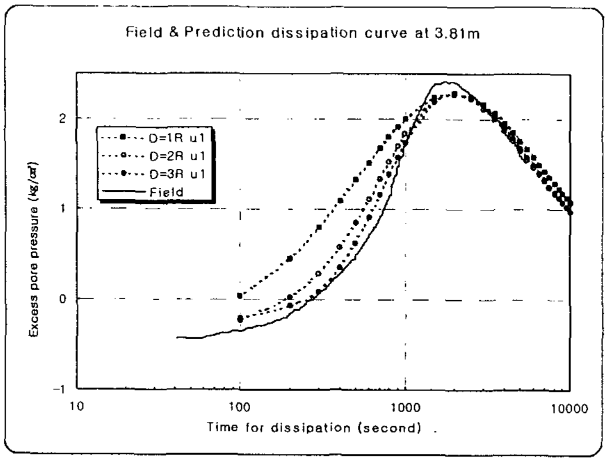


Figure 5.1 Comparison of field and prediction curves at 3.81m, DPH site.

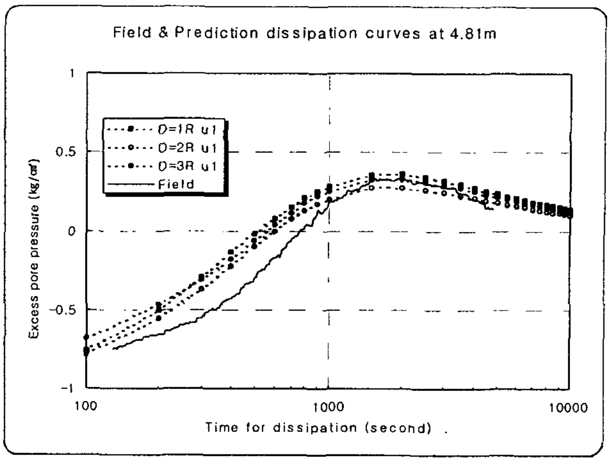


Figure 5.2 Comparison of field and prediction curves at 4.81m, DPH site.

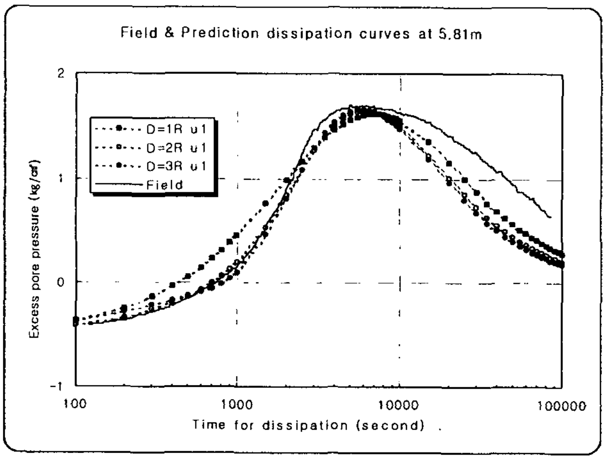


Figure 5.3 Comparison of field and prediction curves at 5.81m, DPH site.

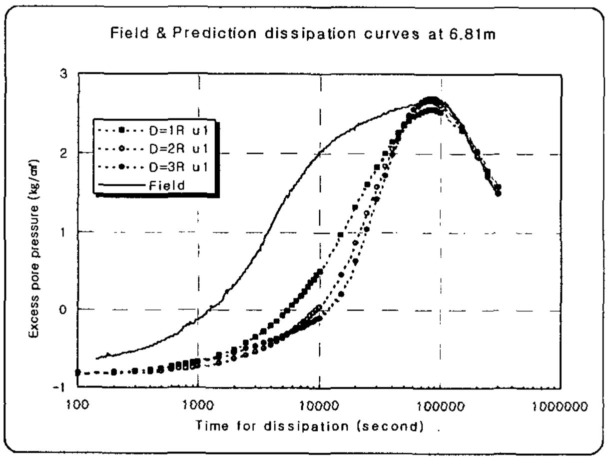


Figure 5.4 Comparison of field and prediction curves at 6.81m, DPH site.

For compare the coefficient of consolidation used in analysis and that inferred from dissipation curve, evaluate c_v using the method suggested by Robertson et al. (1992).

It is assumed that the consolidation process progresses after peak positive excess pore pressure measured and t_{50} is the time at 50% dissipation of the peak positive excess pore pressure.

Table 5.2 Comparison coefficient of consolidation between predicted and evaluated values.

<table>
<tr><th>Depth (m)</th><th>Inner zone radius</th><th>G/Su</th><th>Predicted cv (cm²/sec)</th><th>Evaluated cv (cm²/sec)</th><th>Note</th></tr>
<tr><td rowspan="3">3.81m</td><td>1R</td><td>220</td><td>1.45E-03</td><td rowspan="3">1.20E-03</td><td rowspan="12">Laboratory cv results at preconsolidation stress :
at 2.85m :
2.00E-04
at 5.30m :
1.00E-04</td></tr>
<tr><td>2R</td><td>200</td><td>4.30E-03</td></tr>
<tr><td>3R</td><td>200</td><td>7.50E-03</td></tr>
<tr><td rowspan="3">4.81m</td><td>1R</td><td>200</td><td>2.50E-03</td><td rowspan="3">2.00E-03</td></tr>
<tr><td>2R</td><td>200</td><td>7.00E-03</td></tr>
<tr><td>3R</td><td>200</td><td>1.10E-02</td></tr>
<tr><td rowspan="3">5.81m</td><td>1R</td><td>200</td><td>4.17E-04</td><td rowspan="3">1.20E-04</td></tr>
<tr><td>2R</td><td>198</td><td>1.39E-03</td></tr>
<tr><td>3R</td><td>198</td><td>2.61E-03</td></tr>
<tr><td rowspan="3">6.81m</td><td>1R</td><td>200</td><td>4.00E-05</td><td rowspan="3">3.30E-05</td></tr>
<tr><td>2R</td><td>200</td><td>1.05E-04</td></tr>
<tr><td>3R</td><td>200</td><td>1.83E-04</td></tr>
</table>

Table 5.2 shows that the results from evaluated c_v and c_v used in this analysis is very similar and it is especially similar when the radius of inner zone is 1R.

The coefficient of consolidation about the depth at 5.30m is similar to computer analysis results. But the case of the depth 2.85m, the result somewhat different from obtained analysis results.

6. Summary and Conclusions

In this research, the following conclusions could be made.

1. In dilating soil as stiffness or heavily overconsolidated clay, negative excess pore pressures are developed immediately adjacent to the cone tip. And these are probably surrounded by the outer zone of the positive excess pore pressure developed. In that reason, the dissipation curve changes from negative to positive before a final decrease to zero.
2. In the inner zone, the shear induced excess pore pressure developed. And the distribution of negative excess pore pressure with distance within this zone follows a logarithmic distribution.
3. The outer zone is subjected to isotropic elastic compression. So octahedral normal induced pore pressure developed, which is derived base on cavity expansion theory. And the pore pressure distribution with distance follows a cubic curve.
4. According to computer program analyzed results, when the radius of inner zone is 2R~3R, the dissipation curves agree well with field dissipation curves. But the comparison of coefficient of consolidation between predicted and evaluated is somewhat different to above results. In the case of the inner zone radius is 1R, it agrees well with evaluated values.
5. These predicted coefficient of consolidation are not quite different each other about the radius change from 1R to 3R. And relatively these are reasonable value compare with evaluated values.

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