

# Interpretation of Empirical Cone Factors for Determining Undrained Strength

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## 비배수강도 결정을 위한 콘 지수 연구

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**Abstract** The results of PCPT(Pezococone Penetration Test) are widely used for the estimation of the undrained shear strength, for which the empirical cone factors( $N_{kt}$ ,  $N_{ke}$ ,  $N_{\Delta u}$ ) need to be obtained at each site. In this study, the cone factors were estimated, for the soils at Bookmyun area in Changwon city, using the undrained shear strengths from the unconfined and UU triaxial compression tests. The parametric studies with plastic index and pore water pressure ratio were performed as well.  $N_{kt}$ ,  $N_{ke}$ , and  $N_{\Delta u}$  were estimated in the ranges of 8~40, 7~37, and 1~26 respectively. It was observed that there is a relationship between the cone factors, specially  $N_{\Delta u}$ , and the pore pressure ratio.

**요 약** 콘 관입시험 결과는 현장의 비배수전단강도 결정을 위하여 광범위하게 활용되고 있으며, 이를 위하여 지역 별로 적절한 경험적 콘 지수( $N_{kt}$ ,  $N_{ke}$ ,  $N_{\Delta u}$ )의 결정이 필요하다. 본 연구에서는 창원 북면 지역 지반에 대하여 일축 압축시험 및 비압밀비배수 삼축압축시험 결과를 이용하여 콘 지수를 산정하였으며, 소성지수 및 간극수압비의 관계를 고찰하였다.  $N_{kt}$ ,  $N_{ke}$ ,  $N_{\Delta u}$ 은 각각 8~40, 7~37, 1~26으로 산정되었으며, 간극수압비와 비교적 큰 연관성이 있음이 고찰되었다.

**Key Words** : Piezocone, Undrained strength, Cone Factor, Pore Water Pressure Ratio

## 1. Introduction

The undrained strength to be used in stability analysis depends on the design problem since in-situ undrained strength is affected by such various factors as failure mode, soil anisotropy, strain rate, and stress history. Although an amount of study has been conducted on the interpretation of undrained strength using PCPT(Piezocone Penetration Testing) data, it necessarily requires some empirical content to account for those affecting factors(Su et al. 2002)[1].

The undrained strength from PCPT results is generally estimated through empirical correlations rather than the complicated theoretical methods containing simplifying assumptions regarding the actual soil behavior(Yu et al. 1998, Lunne et al. 1997, Hong et al. 2009, KGS 2005)[2-5]. The empirical correlations adopt the term 'cone factor' based on the concept of the total cone resistance, effective cone resistance, or excess pore pressure. The value of the cone factor is estimated using the undrained strength from the experiments thus it is to vary with area.

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In this study, the cone factor values, based on the various concepts stated above and such experiments as unconfined and triaxial compression testings, were suggested for the soils in Changwon city area. The parametric studies of the cone factors and soil properties were performed as well.

## 2. Methods to determining undrained strength using PCPT data

There are two main categories in which the undrained strength is interpreted using PCPT data; one based on theoretical solutions and the other based on empirical correlations(Su et al. 2002, Lunne et al. 1997)[1,2].

The theoretical solutions result in a relationship in Eq. (1).

$$q_c = N_c \cdot s_u + \sigma_o \quad (1)$$

where  $q_c$  is the cone tip resistance,  $N_c$  is a theoretical cone factor,  $s_u$  is the undrained strength, and  $\sigma_o$  is the in-situ total stress.  $N_c$  is solved based on such theories as the classical bearing capacity theory, the cavity expansion theory(Vesic 1972, Salgado et al. 1997), the strain path method(Baligh 1985), and the finite element method using small or large strain models(Teh and Houlsby 1991, van den Berg 1994)[6-10]. The theoretical solutions have limitations in modeling the real soil behavior although they have provided a useful framework of understanding. Hence, the empirical approaches are generally preferred(Lunne et al. 1997)[3].

The empirical methods can be divided into three groups; using total cone resistance, effective cone resistance, or excess pore pressure.

The undrained strength  $s_u$  using total cone resistance is made from Eq. (2)(Schertmann 1978, Lunne et al. 1985)[11,12].

$$s_u = \frac{(q_t - \sigma_{vo})}{N_{kt}} \quad (2)$$

where  $q_t$  denotes the total cone resistance corrected for

the pore pressure effect, that is called unequal area effect(Lunne et al. 1997)[2].  $\sigma_{vo}$  is the in-situ total vertical stress.  $N_{kt}$  is an empirical cone factor.

Campanella et al.(1982) suggested the correlation Eq. (3) using the effective cone resistance[13].

$$s_u = \frac{(q_t - u_2)}{N_{ke}} \quad (3)$$

where  $u_2$  means the measured pore pressure immediately behind cone tip and  $N_{ke}$  indicates an empirical cone factor.

The excess pore water pressure could be used to estimate  $s_u$  through Eq. (4)(Campanella et al. 1985)[14].

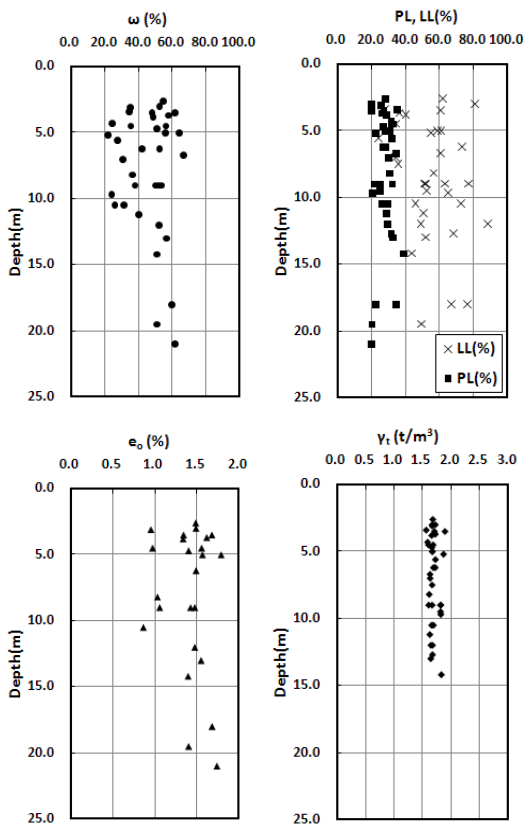
$$s_u = \frac{(u_2 - u_o)}{N_{\Delta u}} \quad (4)$$

where  $u_o$  is the static pore water pressure and  $N_{\Delta u}$  indicates an empirical cone factor.  $N_{\Delta u}$  is theoretically shown to vary between 2 and 20 based on the cavity expansion theory[14].

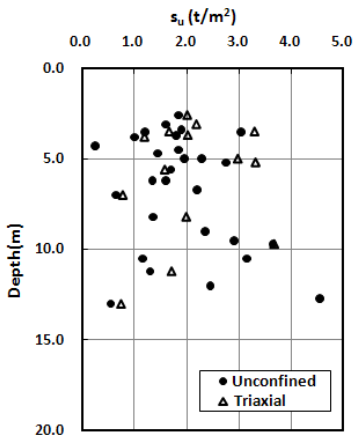
$s_u$  is determined through Eqs. (2) to (4) using the PCPT results and the empirical cone factors( $N_{kt}$ ,  $N_{ke}$ ,  $N_{\Delta u}$ ) which can be obtained from various lab. and field testings performed at each geotechnical area.

## 3. Site and Experimental Results

The lab. tests were conducted together with PCPT for the soils at Bookmyun area in Changwon city. The sub-soil profile is composed of the first layer of sandy silt or silty sand from ground level to 0.6~2.0m depth, the second layer of silty clay with 7.0~12.0m depth, and the third layer of silty sand or gravel with 2.3~5.5m depth. Figs. 1 and 2 show respectively the physical properties and the undrained strength obtained from the unconfined and the UU triaxial compression tests for the soils. The piezocone used in the PCPT is the manufactures of the Geotech. Co. and consists of 60° cone with 10cm<sup>2</sup> base area, a 150cm<sup>2</sup> friction sleeve located above the cone, and the filter element immediately behind the cone tip( $u_2$ ).



[Fig. 1] Physical Properties of Soils

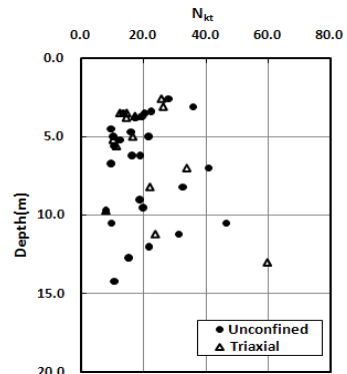


[Fig. 2] Undrained Strength of Soils

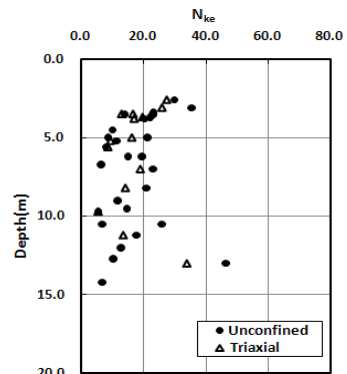
#### 4. Interpretation of Cone Factor

##### 4.1 Values of Cone Factors from Lab. Tests

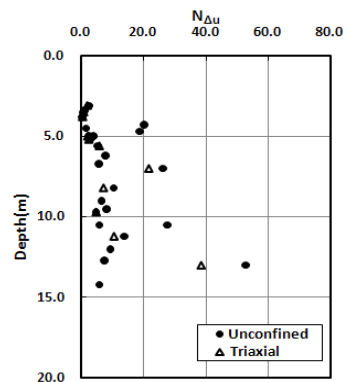
The empirical cone factors ( $N_{kt}$ ,  $N_{ke}$ ,  $N_{\Delta u}$ ), which were obtained through Eqs. 2 to 4 using the undrained strengths from the unconfined and triaxial compression testings, are shown in Fig. 3. The values of  $N_{kt}$ ,  $N_{ke}$ , and  $N_{\Delta u}$  were estimated mainly in the ranges of 8~40, 7~37, and 1~26 respectively.



(a)  $N_{kt}$  with depth



(b)  $N_{ke}$  with depth



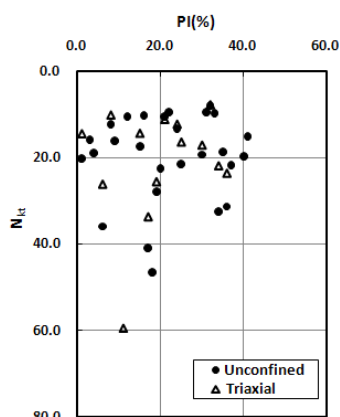
(c)  $N_{\Delta u}$  with depth

[Fig. 3] Variation of Cone Factors with depth

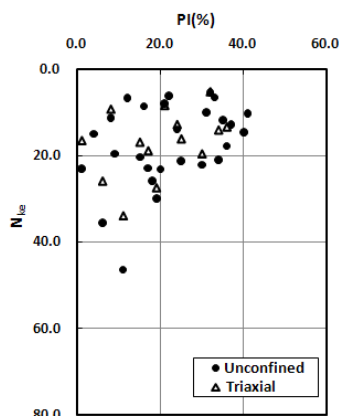
The values showed slightly wider range than the previous study by Hong et al.(2009)[4]. Considering the possible exclusion of the unreliable data, both results are expected to be more close to each other. The cone factors using the unconfined strength are larger than those using the triaxial strength. This is because the unconfined strength is smaller than the triaxial strength.

### 4.2 Cone Factor and Plastic Index

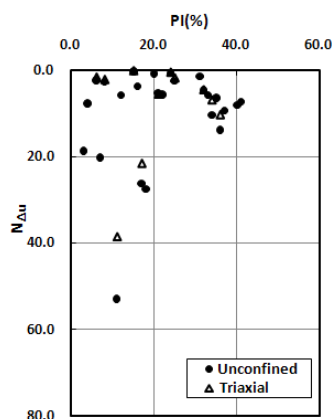
Fig. 4 presents the relationships between the cone factors and the plastic indices.



(a)  $N_{kt}$  with PI



(b)  $N_{ke}$  with PI



(c)  $N_{\Delta u}$  with PI

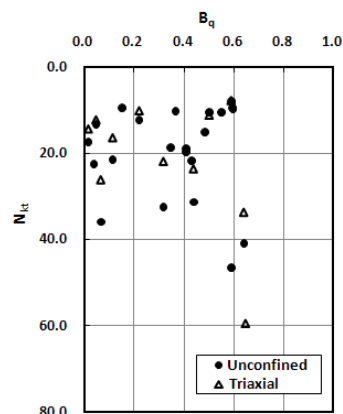
[Fig. 4] Variation of Cone Factors with PI

It seems that the cone factors are not continuous with the plastic indices. Though slight variation of the cone factor values with PI might be appreciated, it is judged that it is not the influence of PI but the influence of depth. This tendency is the same as in most previous studies.

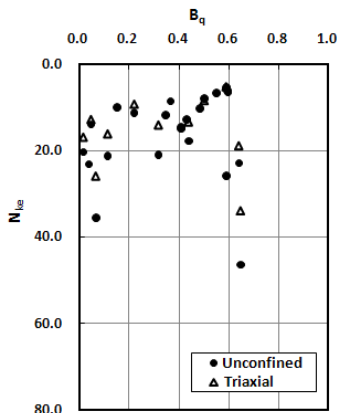
### 4.3 Cone Factor and Pore Pressure Ratio

Fig. 5 indicates the variation of the cone factor and the pore water pressure ratio  $B_q$ (Eq. 5), which is widely used as a parameter for the interpretation of PCPT results.

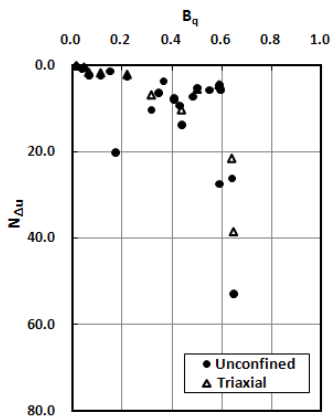
$$B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}} = \frac{\Delta u_2}{q_{cnet}} \tag{5}$$



(a)  $N_{kt}$  with  $B_q$



(b)  $N_{ke}$  with  $B_q$



(c)  $N_{\Delta u}$  with  $B_q$

[Fig. 5] Variation of Cone Factors with  $B_q$

$N_{kt}$  and  $N_{ke}$  generally do not show any remarkable relationship with  $B_q$  while they are likely to decrease with  $B_q$  without several points with low values of  $N_{kt}$  and  $N_{ke}$ , on the other hand  $N_{\Delta u}$  tends to decrease with  $B_q$ , that is similar to the investigations in the previous studies. The pore water pressure ratio  $B_q$ , unlike PI, has a link with the cone factors, specially  $N_{\Delta u}$ . It can be said that the estimation of the cone factors using  $B_q$  is possible.

### 5. Conclusions

In this study, the empirical cone factors  $N_{kt}$ ,  $N_{ke}$ , and  $N_{\Delta u}$ , for the soils at Bookmyun area in Changwon city, were estimated using the undrained strength from the

unconfined and the undrained-unconsolidated triaxial compression testings. The cone factors were investigated with plastic index and pore pressure ratio  $B_q$  as well. The following conclusions could be made.

- $N_{kt}$ ,  $N_{ke}$ , and  $N_{\Delta u}$  were respectively estimated mainly in the ranges of 8~40, 7~37, and 1~26.
- The cone factors using the unconfined strength were larger than those using the triaxial strength due to the difference of their experimental results.
- The cone factors did not show a remarkable continuity with the plastic indices.
- There is a relationship between  $B_q$  and the cone factors, specially  $N_{\Delta u}$ . The cone factors can be estimated using  $B_q$  to a reliable extent.

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<Research Interests>

Geotechnical Engineering, Soils and Foundations, Ground Exploration and Testing, Constitutive Relations, Numerical Analysis, Underground