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Undrained shear strength from cone penetration test

Hisham T. Eid & Timothy D. Stark
Department of Civil Engineering, University of Illinois at Urbana-Champaign, Ill., USA

ABSTRACT: Unconfined compression and cone penetration test results were used to develop a relationship between undrained shear strength and cone tip resistance for the soft to stiff, saturated glacial clays of downtown Chicago, Illinois. The cone factor relating the unconfined compression strength to the cone tip resistance, termed N_{kuc}, has an average value of 15.5 for Chicago soft to stiff, saturated clays. Additional values of N_{kuc} were compiled from the literature for clays with similar consistency. The unconfined compression strength for soft to stiff clays with plasticity indices of 15 to 50 can be estimated using the cone penetration test results and an N_{kuc} value of 16. For saturated clays in this plasticity range, the unconfined compression strength provides a practical estimate of the mobilized undrained shear strength for foundation design, and embankment and excavation stability analyses.

1 INTRODUCTION

In Chicago, the unconfined compression test (UC) has been frequently used to estimate the undrained shear strength of the glacial clays since construction started on the Chicago Subway in 1939. Clays with very soft to medium consistencies are limited to a zone extending five miles or less from the shore of Lake Michigan and have a thickness between 3 and 15 meters. Stiff to hard clays are usually encountered before bedrock is reached. The cone penetration test (CPT) provides a quick insight into soil stratigraphy and is frequently used during initial site investigations to design an efficient boring and sampling program. An empirical correlation between cone penetration tip resistance and unconfined compressive strength is developed to facilitate usage of the CPT in design and construction activities in the Chicago area.

2 EXISTING CORRELATIONS

CPT results are used to estimate the undrained shear strength of clays through empirical correlations and/or theoretical solutions (Baligh et al. 1980). The most commonly used formula is based on the bearing capacity theory proposed by Terzagi (1943) and rewritten as:

$$q_c = N_k \cdot S_u + \sigma_{vo}$$

where q_c is the cone tip resistance, N_k is the empirical cone factor, S_u is the undrained shear strength, and σ_{vo} is the total vertical stress at the depth of penetration. The wide scatter in the empirical and theoretical N_k values presented in the literature shows that no single value of N_k covers all types of clays, penetrometers, and test conditions (Amar et al. 1975; Schmertmann 1975). However, for a given clay deposit, penetrometer, and test condition, it seems likely that there is a unique relationship between cone tip resistance and undrained shear strength, e.g., Lunne et al. (1976), Koutsoftas and Fischer (1976), and Stark and Delashaw (1990).

Data collected by Lunne and Kleven (1981) and Jamiolkowski et al. (1982) show that for very soft to medium clays the cone factor based on S_u measured using a field vane shear test (N_{kfv}) decreases with increasing plasticity index and ranges from 9 to 26. Bjerrum (1972) reviewed sixteen well-documented embankment, footings, and excavation failures through cohesive soils and developed the field vane correction factor, μ_{fv}. The correction factor reflects the influence of soil disturbance, progressive yielding, mode of shear, and strain rate on the difference between the undrained shear strength measured using the field vane test, S_u (FV), and the undrained shear strength mobilized at full-scale instability. If the vane shear strength values are corrected using Bjerrum's correction factor, the resulting corrected cone factor

(N^*_{kfv}) appears to be independent of plasticity index. As shown in Figure 1, N^*_{kfv} values are between 8 and 24, with an average of approximately 15.

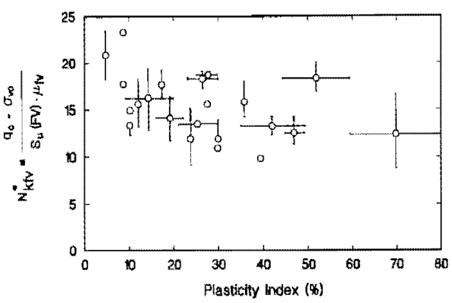


Figure 1. Previously published corrected field vane cone factors (after Lunne and Kleven 1981, and Meigh 1987)

Stark and Delashaw (1990) developed a correlation between undrained shear strength from unconsolidated-undrained triaxial tests, S_u (UU), and cone tip resistance. They studied nonfissured normally to lightly overconsolidated clays from twenty one different sites with an emphasis on San Diego, California. Unconsolidated-undrained (UU) triaxial compression test results were obtained using 38-mm-diameter specimens. The cone factor relating UU triaxial strength to the cone tip resistance, termed N_{kuu}, ranges from 8.5 to 16.5, with an average value of approximately 12 (Figure 2).

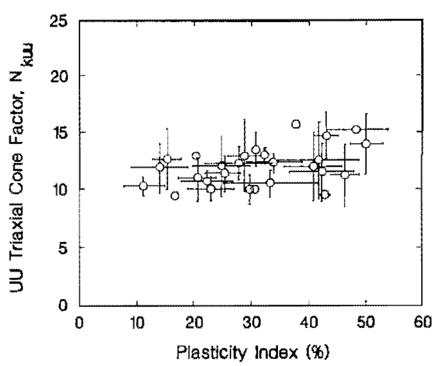


Figure 2. Variation of UU triaxial cone factor with plasticity index (after Stark and Delashaw 1990)

The values of N_{kuu} show less scatter than N^*_{kfv} values. The reduction in scatter is probably due to the use of tip resistance values measured using only a standard electrical cone and the repeatability and simple interpretation of UU triaxial tests.

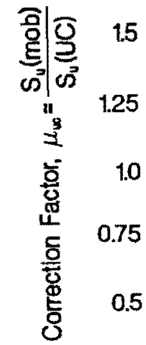
Terzaghi et. al (1996) showed that values of cone factor for stiff fissured clays based on UU compression triaxial tests on 100-mm-diameter specimens range from 11 to 30. The more fissures included in the specimen and the more local softening due to a slower strain rate during the laboratory undrained shearing, the lower the measured laboratory undrained shear strength compared to the cone resistance. Both effects should increase with the plasticity of the clay. Therefore, the value of the cone factor for stiff fissured clays depends on fissure spacing and plasticity.

3 NEW EMPIRICAL CONE FACTOR

A number of different techniques for measuring the undrained shear strength (field vane, unconfined compression, consolidated-undrained triaxial, and unconsolidated-undrained triaxial) were considered during this study. Despite the limitations of the unconfined compression test, the undrained shear strength obtained from this test is widely used in the geotechnical profession and in particular in Chicago. The popularity of the unconfined compression test is due to the ease in performing the test and interpreting the results compared to the vane shear test and other laboratory undrained shear strength tests.

Figure 3 compares the undrained shear strength from the unconfined compression test, S_u (UC), to the average mobilized strength along the surface of sliding of failed embankments S_u (mob). The S_u (UC) data for the cases summarized in Figure 3 correspond to tube samples of D to B quality (Terzagi et al. 1996). The data in Figure 3 show that specimen disturbance in the unconfined compression test leads to S_u (UC) values that are smaller than S_u (FV). However, in the plasticity index range of 20 to 60%, μ_{uc} is close to unity. Therefore, for saturated clays in this plasticity range, the unconfined compression strength from tube samples of D to B quality provide a practical estimate of the mobilized undrained shear strength for foundation design, and embankment and excavation stability analyses (Terzagi et al. 1996).

Owing to the popularity of the UC test and the direct correlation between S_u (UC) and the mobilized undrained shear strength in the field, a new cone factor that relates the unconfined compressive strength to the cone tip resistance (q_c) is presented herein and referred to as N_{kuc}. The undrained shear strength data was obtained using 35 and 50 mm-diameter Shelby tube samples. Only cone soundings using a standard electrical cone advanced at approximately 2 cm/sec and in accordance with ASTM D3441(ASTM 1990) were used in the correlation. The electric cones have an apex angle of 60 degrees and a projected area of 10 cm^2.



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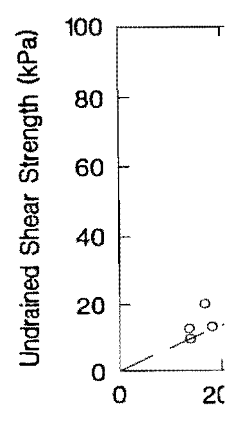

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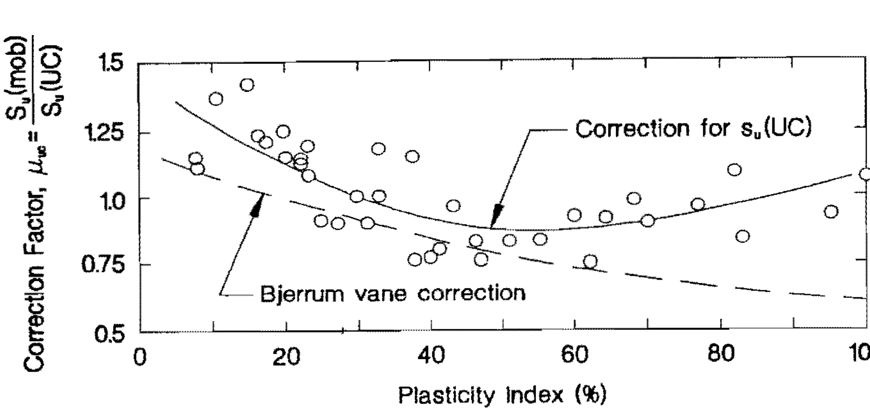

Figure 3. Correction factor for undrained shear strength from unconfined compression test on tube samples (after Terzaghi et al. 1996).

3.1 *Chicago, Illinois sites*

To facilitate use of the CPT in the Chicago area, a research program was initiated to develop a cone factor (N_{kuc}) for Chicago soil deposits. Nine sites in downtown Chicago were studied to develop the cone factor. These sites/projects are the Chicago central library, Evanston tunnel, McCormick Place 3, Museum of Contemporary Art, Navy pier, Northwestern University geotechnical test site, Canal & Harrison mail facility, Rush Presbyterian hospital, and University of Illinois engineering research facility.

The subsoil of the Chicago area consists of a series of glacial clays, each somewhat stiffer than the one above. Beneath the downtown districts of Evanston and Chicago, the clays have very soft to medium consistencies for thicknesses up to 15 meters. Hard clays are usually encountered before bedrock is reached, but many deposits of waterbearing sands and gravel are present near the rock (Peck and Reed 1954). Cone penetration tests at depths up to 21 meters were used to investigate the very soft to stiff clay layers. Stiffer clays were not considered because of the uncertainty in interpreting cone measurements in them. The average liquid limit, plastic limit, and clay-size fraction (% by weight < 0.002 mm) of Chicago clays are 32%, 17%, and 13%, respectively.

Figure 4 shows the net cone resistance ($q_c - \sigma_{vo}$) and the corresponding undrained shear strength from unconfined compression tests at the nine Chicago sites. It can be seen that the average value of N_{kuc} for Chicago soft to stiff, saturated clays is 15.5. Some of the scatter around the trend line is probably due to the difference in the disturbance of the undrained compression specimens.

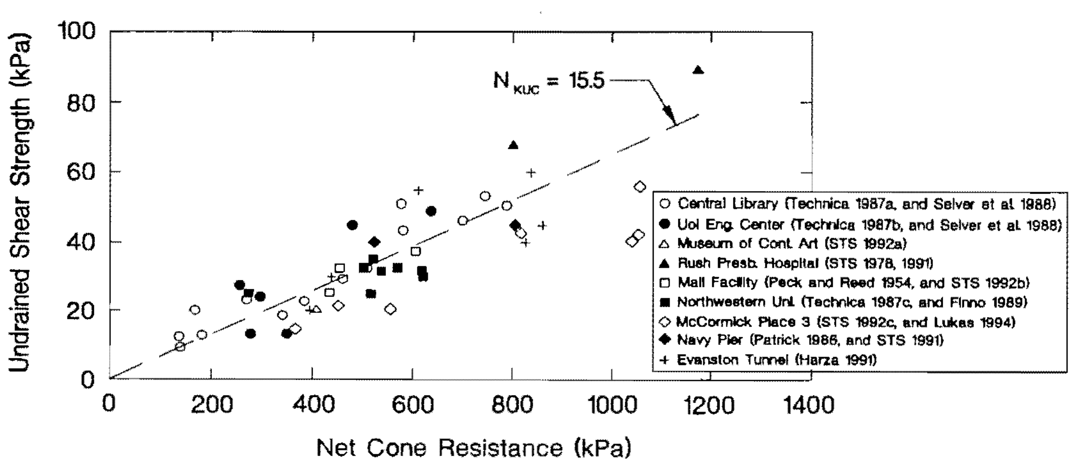

Figure 4. UC cone factor as a function of net cone resistance and undrained shear strength for Chicago sites

3.2 *Variation of the cone factor with plasticity index*

Additional data were compiled from the literature and values of N_{kuc} were calculated for clays with similar consistency to investigate the accuracy of the N_{kuc} values for Chicago clays and the variation of the cone factor with plasticity index (PI). Only test areas with unconfined compressive strengths measured on test specimens having a degree of saturation at or near 100 percent were selected. In addition, only cone soundings, using a standard electric cone advanced at approximately 2 cm/sec and in accordance with ASTM D3441, were used. The test areas and source of the data are shown in Figure 5.

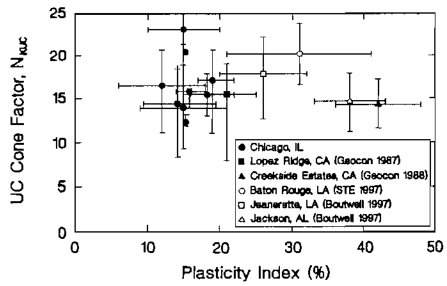

Figure 5. Variation of UC cone factor with plasticity index

Figure 5 shows the variation of N_{kuc} with the plasticity index. Each data symbol represents the average value of PI and N_{kuc} calculated at each testing area, while the lines surrounding each point illustrate the range of PI and N_{kuc}. It can be seen that the values of N_{kuc} range from 8 to 25 for all of the sites, with an average value of approximately 16.

To facilitate determination of the undrained shear strength, the data were plotted in terms of net cone resistance and undrained shear strength for each site in Figure 6. It can be seen that the majority of the data plot along a straight line corresponding to a value of N_{kuc} equal to 16. This average value of N_{kuc} is comparable to the corrected field vane factor N_{kfv} (Figure 1). In addition, the correction factor μ_{uc} shown in Figure 3 is equal to approximately unity in the plasticity index range over which the average N_{kuc} was approximated to be 16 (Figure 5). As a result, for sites with soft to stiff clays with a plasticity index ranging from 15 to 50 percent, the mobilized field undrained shear strength can be estimated using N_{kuc} approximately equal to 16. Therefore, the resulting undrained shear strength values do not have to be corrected, as suggested by Bjerrum (1973) for the field vane test results, to estimate the mobilized undrained shear strength.

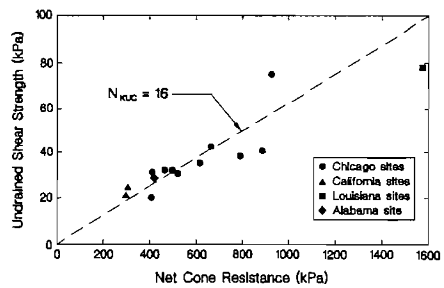

Figure 6. UC cone factors as a function of net cone resistance and undrained shear strength

4 CONCLUSIONS

The main objective of this research was to develop an empirical cone factor for the soft to stiff, saturated glacial clays of downtown Chicago, using the tip resistance from electrical cone penetration tests conducted in accordance with ASTM Standard D3441 and values of undrained shear strength measured in unconfined compression tests. The following conclusions are based on studying nine different sites in downtown Chicago and additional sites with clays of similar consistency.

1. The cone factor, N_{kuc}, relating the unconfined compressive strength to the cone tip resistance has an average value of 15.5 for Chicago soft to stiff, saturated clays.

2. The unconfined compression strength for soft to stiff clays with plasticity indices of 15 to 50 percent for many sites including Chicago can be estimated using cone penetration test results and an N_{kuc} value of 16.

3. For soft to stiff, saturated clays with plasticity index ranges from 15 to 50 percent, the unconfined compressive strength calculated using the cone resistance and N_{kuc} equal to 16 provides a practical estimate of the mobilized undrained shear strength for foundation design, and embankment and excavation stability analyses.

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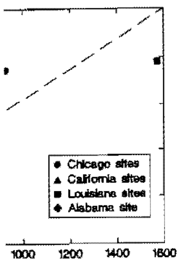

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