Undrained shear strength from cone penetration tests

La résistance au cisaillement non drainée à partir des essais pénétrométriques

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SYNOPSIS Results of unconsolidated-undrained triaxial tests, field vane shear tests and cone penetration tests have been used to develop correlations between undrained shear strength and cone resistance for a soft to medium alluvial clay in the Lopez Canyon area of San Diego. When comparing UU triaxial results with cone resistance, the average cone factor was 11 with a standard deviation of 1.5. When comparing corrected field vane shear strength with cone resistance, the average cone factor was 13 with a standard deviation of 1.0. The difference in the measured values of shear strength is most likely due to soil anisotropy and/or differences between triaxial and vane shear tests. For design, an average cone factor of 12 is recommended for alluvial clay with similar characteristics as that found in Lopez Canyon.

INTRODUCTION

In Southern California, the cone penetration test (CPT) is frequently used during initial site investigations to provide information for an efficient boring and sampling program. The CPT provides a quick insight to soil stratigraphy and also identifies soil layers that might be problematic and require additional testing during the remainder of the investigation. Laboratory testing programs are then designed to measure the engineering properties of these soil layers using high quality samples obtained from soil borings located using the CPT results. Currently in San Diego, most of the geotechnical design is based on the results of laboratory tests. In an effort to incorporate the CPT results into the geotechnical design process, correlations between cone penetrometer resistance and undrained shear strength are being developed for soil deposits in the San Diego area.

For clays, the undrained shear strength is derived from CPT results using theoretical solutions and/or empirical correlations. Baligh et al. (1980) present a comprehensive overview of the different theories which can be grouped into the following three main categories: 1.) bearing capacity, 2.) cavity expansion and 3.) steady penetration.

The bearing capacity analysis of the cone penetration test is based on Prandtl's (1920) fundamental solution for a strip footing on the surface of a rigid-plastic material at incipient failure. The bearing capacity solutions employ the following equation:

$$q_c = N_c \, S_u + \sigma_{vo} \tag{1}$$

where q_c = cone resistance

N_c = bearing capacity factor

S_u = undrained shear strength

σ_{vo} = total vertical stress.

A number of expressions for N_c have been developed by researchers and they incorporate various combinations of shape, depth and/or geometry factors. Table 1 presents a summary of N_c values calculated for a standard cone with an apex angle of 60 degrees.

TABLE I - Bearing Capacity Factors for Cone Penetration in Clays (Adapted from Baligh, 1975)

Reference	N_c
Terzaghi (1943)	9.3
Mitchell and Durgunoglu (1973)	9.6
Meyerhof (1961)	10.4
Begemann (1965)	13.4
Anagnostopolous (1974)	17.0

The cavity expansion approach is based on the solution proposed by Bishop et al. (1945) for the expansion of a cylindrical cavity in an elastic perfectly plastic material, starting from zero radius. Gibson (1950) and Vesic (1972) extended the solution to the problem of bearing capacity at depth, making assumptions concerning the stress field around the cone. The expression for cone penetration resistance presented by Vesic (1972) is:

$$q_c = N_c \, S_u + \sigma_{oct} \tag{2}$$

where $N_c = 1.33\,(1 + \ln G/S_u) + 2.57$

G = undrained shear modulus

σ_{oct} = octahedral normal stress = $1/3\ (\sigma_{vo} + 2\ \sigma_{ho})$

σ_{ho} = total horizontal stress.

The steady penetration approach presented by Baligh (1975) expresses the cone resistance per unit distance as the sum of the work required to push the cone tip and the work to open a cylindrical cavity behind the cone. Baligh uses the following equation for cone resistance:

$$q_c = N_c\ S_u + \sigma_{ho} \qquad (3)$$

where $N_c = 1.2(5.71 + 3.33\delta + \cot \delta) + (1 + \ln I_R)$

2δ = apex angle of cone tip in radians

I_R = Rigidity index = G/S_u.

These three methodologies employ a form of the bearing capacity equation with different expressions for the total overburden pressure and N_c, to determine the undrained shear strength. In addition, an empirical equation which is similar to equation (1) is frequently used in practice to relate cone resistance to undrained shear strength. The empirical expression commonly used in practice is:

$$q_c = N_k\ S_u + \sigma_{vo} \qquad (4)$$

where N_k = empirical cone factor.

Previous data collected by Lunne and Kleven, (1981), and Jamiolkowski et al. (1982) show that the empirical cone factor, N_k, decreases with plasticity index and ranges from 9 to 26 when S_u is measured using a field vane shear test.

If the vane shear strength values are corrected using Bjerrum's (1972) field correction factor, μ, the resulting corrected cone factor ($N_k{*}=N_k/\mu$) appears to be independent of plasticity index and shows considerably less scatter than N_k.

As shown in Figure 1 the majority of the published $N_k{*}$ values fall between 11 and 19 with an average of approximately 15. However, the values of $N_k{*}$ vary considerably depending on the type of cone, test procedure, and most importantly the soil deposit. As a result, values of corrected cone factor need to be developed for different soil deposits and test procedures.

TEST SITE

To facilitate the use of CPTs in the San Diego

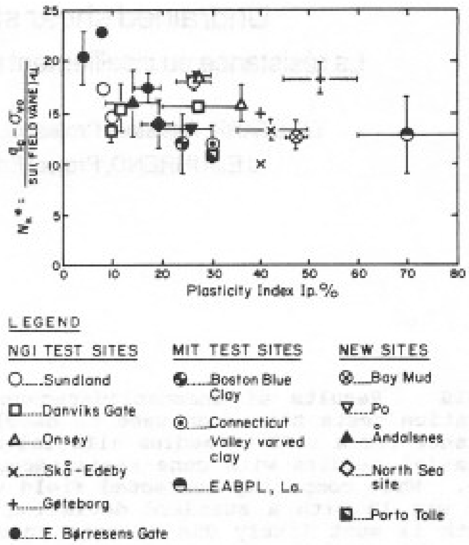

Figure 1. Previously published corrected cone factors (adapted from Lunne and Kleven, 1981)

area, a research program was initiated to develop cone factors for local soil deposits. The first site investigated in this ongoing study is the proposed Lopez Bridge Crossing in the Sorrento Valley area of San Diego County. The proposed bridge crossing will necessitate the construction of a roadway embankment fill approximately 215 m in length and varying in height from 6 to 9 m.

The project site lies within the general confluence of two major northeast-southwest trending alluviated canyons. The canyon alluvium ranges in thickness from approximately 3 to 15 m with the depth increasing toward the middle of the canyon. The alluvium consists of a young, soft to medium silty clay with low plasticity.

The field investigation for the Lopez Bridge Crossing site consisted of 12 cone pentrometer soundings, 13 borings and six field vane shear tests. The cone soundings were performed by Earth Technology Corporation using a standard electrical cone. Exploratory borings were drilled within 6 m of four cone penetration soundings to obtain relatively undisturbed, 7.6 cm diameter shelby tube samples for laboratory testing to develop cone factors relating cone resistance to undrained shear strength.

LABORATORY TEST RESULTS

Classification tests, a consolidation test and three unconsolidated-undrained (UU) triaxial tests were performed in accordance with ASTM standards on each shelby tube sample. The alluvial clay has an average liquid limit and plasticity index of 40 and 20, respectively, and was classified as a CL. The clay was also found to be normally consolidated to slightly overconsolidated, with an overconsolidation ratio, OCR, varying from 1 to 2.

Undrained shear strength values were measured using 3.6 cm diameter triaxial specimens and the resulting values of undrained strength ratio, S_u/σ'_{vc}, ranged from 0.24 to 0.43 where σ'_{vc} is the effective consolidation pressure. These values are in good agreement with the relationship of $S_u/\sigma'_{vc} = (0.23\pm0.04)(OCR)^{0.8}$ presented by Jamiolkowski et al. (1985). The sensitivity of the clay ranged from 3 to 5 based on the results of the field vane shear tests.

Values of undrained shear modulus, G, and Young's modulus, E, were estimated using the tangent modulus from UU triaxial stress strain curves and a Poisson's ratio of 0.5. The average value of E/S_u and G/S_u were calculated to be 150 and 50, respectively. However, due to disturbance, the values of undrained modulus determined from laboratory compression tests are usually half to one-quarter of the in-situ modulus. Thus, data from Duncan and Buchignani (1976) were also used to estimate a value of E/S_u equal to 600 which corresponds to a G/S_u value of 200.

CONE CORRELATIONS USING UU TRIAXIAL TEST RESULTS

To investigate the applicability of the bearing capacity, cavity expansion and steady penetration solutions to estimating S_u, values of N_c for each method were back-calculated and compared to values calculated using the theoretical expressions for N_c.

Using the values of S_u obtained from unconsolidated-undrained triaxial tests, values of N_c were back-calculated using equation 1. The average back-calculated value of N_c was 11 with a standard deviation of 1.5. From Table 1 it appears that Meyerhof's (1961) theoretical expression for N_c gives the best estimate of N_c, 10.4, using values of S_u from UU triaxial tests. Using the cavity expansion expression for q_c, (equation 2), and an assumed earth pressure coefficient of 0.5 to estimate the total horizontal stress, values of N_c were back-calculated. The average value of N_c was 11.8 with a standard deviation of 3.5. The value of N_c based on Vesic's (1972) theoretical expression was 10.9 using an estimated G/S_u ratio of 200, and an average of 9.1 when values of G/S_u from triaxial tests were used.

Values of N_c were also back-calculated using Baligh's (1975) steady penetration approach (equation 3), and an assumed earth pressure coefficient of 0.5. The average value of N_c was 12.4 with a standard deviation of 3.7. The values predicted using Baligh's theoretical expression for N_c were 17.3 and 15.9 using the estimated and measured ratios of G/S_u, respectively.

As shown in Table 2, the cavity expansion and steady penetration solutions yielded similar back-calculated values of N_c using values of S_u from triaxial tests. Due to the difficulties in estimating and measuring appropriate values of undrained shear modulus, the theoretical expressions for N_c showed considerable scatter (9.1 to 17.3). However, the cavity expansion solution appears to be in slightly better agreement with the back-calculated values than the steady penetration solution.

TABLE 2 - Values of N_c using Theoretical Solutions for Cone Penetration Tests

Solution	Back-Calculated N_c		Theoretical N_c	
	Triaxial S_u	Vane S_u	Estimated G/S_u	Triaxial G/S_u
Bearing Capacity	11.0	13.0	--	--
Cavity Expansion	11.8	14.9	10.9	9.1
Steady Penetration	12.4	15.0	17.3	15.9

Using the values of S_u obtained from unconsolidated-undrained triaxial tests and σ_{vo} equal to the total overburden pressure, values of N_k were also back-calculated using the empirical approach, (equation 4), and are plotted in Figure 2. As shown these values are at the lower end of the published range of values and have an average value of 11 and a standard deviation of 1.5.

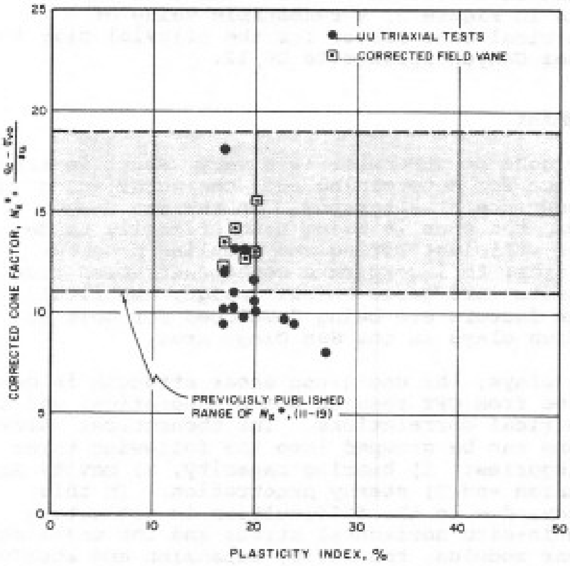

Figure 2. Corrected cone factors derived from UU triaxial tests and field vane shear tests - Lopez Canyon

CONE CORRELATIONS USING FIELD VANE SHEAR TEST RESULTS

When a similar analysis is performed using field vane shear strengths, somewhat different values of N_c are obtained. This is due to the corrected vane shear strengths being slightly lower than the laboratory UU triaxial strengths. The average value of S_u from the field vane and UU triaxial tests were 22.7 kPa and 32.0 kPa, respectively. Typically, due to disturbance, shelby tube samples would show a lower strength than field vane tests. In this case, the measured difference in shear strength is believed to be caused by soil anistropy and/or measurement errors in the field vane shear test.

Using the corrected values of S_u from the field vane shear tests, values of N_c were back-calculated using the bearing capacity solution (equation 1), the cavity expansion solution (equation 2), the steady penetration solution (equation 3) and are shown in Table 2. From a comparison of Tables 1 and 2, it can be seen that the N_c value using the bearing capacity solution and the vane data, agrees well with Begemann's (1965) N_c value of 13.4. Table 2 also reveals the cavity expansion and steady penetration solutions again yielded similar back-calculated values of N_c that were slightly larger than the values back-calculated using the bearing capacity solution.

Using the corrected vane shear strengths and σ_{vo} equal to the total overburden pressure, values of N_k* were also back-calculated using the empirical approach, (equation 4), and are plotted in Figure 2. As shown, these values are in very good agreement with the published range of values and have an average value of 13 and a standard deviation of 1.5. Based on all the data in Figure 2, a reasonable value of empirical cone factor for the alluvial clay in Lopez Canyon appears to be 12.

SUMMARY

The cone penetrometer is a very useful in-situ device for determining soil characteristics and subsurface stratigraphy. In the San Diego area, the cone is being used primarily to design efficient boring and sampling programs. In order to incorporate cone penetration test results into geotechnical design, empirical cone factors are being developed for soft to medium clays in the San Diego area.

For clays, the undrained shear strength is derived from CPT results using theoretical and/or empirical correlations. The theoretical solutions can be grouped into the following three categories: 1) bearing capacity, 2) cavity expansion and 3) steady penetration. In this study, due to the difficulties in estimating the in-situ horizontal stress and the undrained shear modulus, the cavity expansion and steady penetration theories showed considerable scatter in the estimation of N_c (Table 2). As a result, the empirical equation (4), which is similar to the bearing capacity solution, was used to relate cone resistance to undrained shear strength.

Values of N_k and N_k* were back-calculated based on triaxial undrained shear strengths as well as field vane shear strengths. The average value of the empirical cone factor calculated using UU triaxial test results was 11 with a standard deviation of 1.5 whereas the field vane shear tests yielded an average value of 13 with a standard deviation of 1.0. Both of these values are in good agreement with previously published empirical cone factors.

For geotechnical design involving soft to medium alluvial clays with similar characteristics as that found in the Lopez Canyon area of San Diego, it is recommended that equation (4) with a cone factor of 12 be used to obtain reasonable values of undrained shear strength.

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