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Determination of undrained shear strength using piezocone penetration test in clayey soil for bridge foundation

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Abstract: In order to obtain the reasonable undrained shear strength S_u for geotechnical analyses of bridge foundations in Yangtze River floodplain clayey soils, a site-specific study is conducted using the imported piezocone penetration test (CPTu) with dissipation phases at the Fourth Nanjing Yangtze River Bridge construction sites. Taking the values of S_u from laboratory tests as references, several existing S_u-predicted methods based on CPTu are compared and evaluated. To verify the presented cone factor N_k, additional test sites are selected and examined. The results show that the values of cone factors such as N_{kt}, N_{ke}, and $N_{\Delta u}$, depend on the shear test mode and disturbance. Generally, the values of N_{ke} show more scattering than those of N_{kt} and $N_{\Delta u}$. For the stratified and layered sediments of the Yangtze River floodplain, it is recommended using the net cone resistance q_T to estimate S_u and the preliminary cone factor values N_{kt} are from 7 to 16, with an average of 11. It is also confirmed that the CPTu test, as a new technique in site characterization, can present reasonable parameters for bridge foundations.

Key words: undrained shear strength; piezocone penetration test; clayey soil; cone factor; bridge foundation

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Bridge foundations are subjected to a complex array of axial compression, uplift, lateral movement and torsion loading under static, cyclic, dynamic, or seismic modes, or all of those modes[1]. As a consequence, all the soil characterization should be investigated using proper methods, for example, the highly nonlinear and anisotropic stress-strain-strength-time behavior of soils. However, most bridge foundation designers rely solely on boring tests to provide geotechnical data for bridge foundation design and only a few laboratory tests are supplemented, which are quite unrealistic and inappropriate due to the difficulties in obtaining the original soil state through routine drilling practices.

As a complement or an alternative measure to soil boring and laboratory tests, piezocone penetration tests (CPTu) with dissipation phases are particularly useful for geotechnical site investigation as they can provide approximately simultaneous measurements of tip resistance q_T, sleeve friction f_s, and pore pressure[2-3]. The piezocone method has gained popularity in the Euro-American countries. However, it was rarely used in China in the past two decades due to the lack of equipment and corresponding application studies[4-7]. Moreover, the CPTu data require a good estimate of correlation coefficients to determine soil parameters, which depends on the geological formation and can be site-specific. The database of piezocone tests in China is very important for the validation of existing CPTu-based methods.

The undrained shear strength S_u is one of the important parameters for assessing the deformation and strength of clayey soils. It is generally determined by the field vane (tests) or various laboratory tests with the disadvantages of time consumption and inaccuracy. In this paper, aiming to estimate the S_u-value of clayey deposits for bridge foundation design, a series of CPTu and laboratory tests are carried out at the site of the Fourth Nanjing Yangtze River Bridge. The applicability of the cone penetration test (CPT) or CPTu-based prediction methods is evaluated and verified. Relevant correlations between CPTu measurements and S_u are presented.

1 Methods and Materials

1.1 Study area

The Fourth Nanjing Yangtze River Bridge is approximately 20.5 km north to the Nanjing Great Bridge between the towns of Longpao and Qixia, where the north and south cable anchorages are constructed respectively at the two sides of the Nanjing Yangtze River, as shown in Fig. 1. The construction region belongs to the floodplain of the lower reaches of the Nanjing Yangtze River. The ground surface is flat and generally inclines from west to east with an average elevation of 3 to 5 m. The ground water depth is about 0.85 to 1.35 m, fluctuating with tidal motion and seasonal variation. The geological sketch is marked by the deposits of the Yangtze River delta, which consist of alluvial, diluvial, silt, and lacustrine. The Quaternary deposits, which range from late pleistocene to Holocene, primarily consist of alternating clay to silty clay, slits and sands, and gravel. In a typical vertical profile of the Quaternary deposits, the deposit varies in sequences of silty clay, mucky silty clay, silt mixtures, sand mixtures and gravels. The thickness of the Quaternary deposits varies greatly from less than 10 m to greater than tens of meters.

1.2 Methods for estimating S_u from CPT/CPTu

Numerous theoretical or empirical correlations have been developed for S_u estimation from CPT or CPTu[8]. The available empirical approaches for S_u interpretation from CPTu can be mainly grouped into three categories as follows:

1) S_u estimation using net cone resistance;

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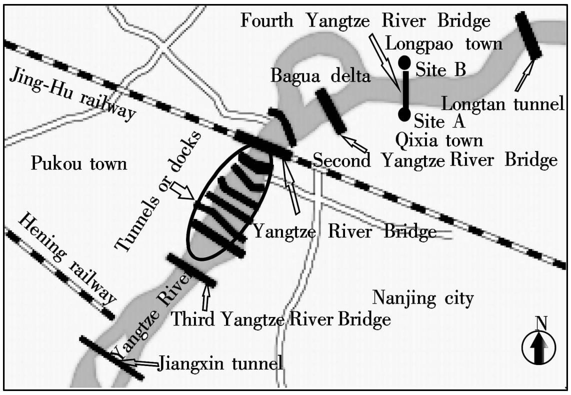


Fig. 1 Location of the Fourth Nanjing Yangtze River Bridge

2) S_u estimation using effective cone resistance;

3) S_u estimation using excess pore pressure.

The corresponding equations are listed respectively as follows:

$$S_u = \frac{q_T - \sigma_{v0}}{N_{kt}} \tag{1}$$

$$S_u = \frac{q_e}{N_{ke}} = \frac{q_T - u_2}{N_{ke}} \tag{2}$$

$$S_u = \frac{u_2 - u_0}{N_{\Delta u}} = \frac{\Delta u}{N_{\Delta u}} \tag{3}$$

where q_T is the net tip resistance with pore pressure correction using the net area ratio, that is, $q_T = q_c + u_2(1 - a)$, and parameter a should be obtained from laboratory chamber calibration, and in this study, $a = 0.8$; σ_{v0} represents the total overburden stress at the cone tip level; u_2 is the pore pressure measured just behind the shoulder; u_0 is the equilibrium pore pressure; N_{kt}, N_{ke}, and $N_{\Delta u}$ are empirical cone factors.

The above values are generally determined by the comparison of CPTu data with measurements of undrained shear strength in field vane or laboratory measurements. The back-calculated values of N_{kt} in literature vary between 7 and 32 for a number of reference S_u tests[9-10]. Comparatively, the values of N_{ke} seem more uncertain varing between 1 and 13[2,9,11]. In general, it is not recommended to estimate S_u using q_e[8], especially for soft normally consolidated clays where q_e is always small and sensitive to small errors in q_c or u_2 measurements, or for heavily overconsolidated deposits where B_q is small or even negative. S_u estimation from the excess pore pressure using Eq. (3) may therefore be more accurate, where $N_{\Delta u}$ varies between 2 and 20 depending on the site-specific characterization.

According to Ref. [8], if little experience is available and S_u is estimated from q_T and N_{kt}, it is suggested that N_{kt} vary from 15 to 20. For a more conservative estimate, N_{kt} should be close to the upper limit. For normally and lightly overconsolidated clays, N_{kt} can be as low as 10. For stiff fissured clay, N_{kt} can be as high as 30. If deposits consist of very soft clays and S_u is estimated from Δu_2 and $N_{\Delta u}$, then $N_{\Delta u}$ should be set from 7 to 10.

1.3 Test procedure

In order to evaluate the reliability of the CPTu-based prediction methods, six CPTu tests with depth from 35 to 40 m are carried out at the south cable anchorage site (site A, Fig. 1). Another eight CPTu tests with depths up to 40 m are performed at the north anchorage site (site B, Fig. 1). Several laboratory tests are also conducted using high quality samples, including the direct simple shear test (DSS), the consolidated quick direct shear test (CDS), and the unconsolidated undrained (UU) triaxial compression test. Among all these methods, the testing program and procedure of CPTu in this study is specially introduced as follows.

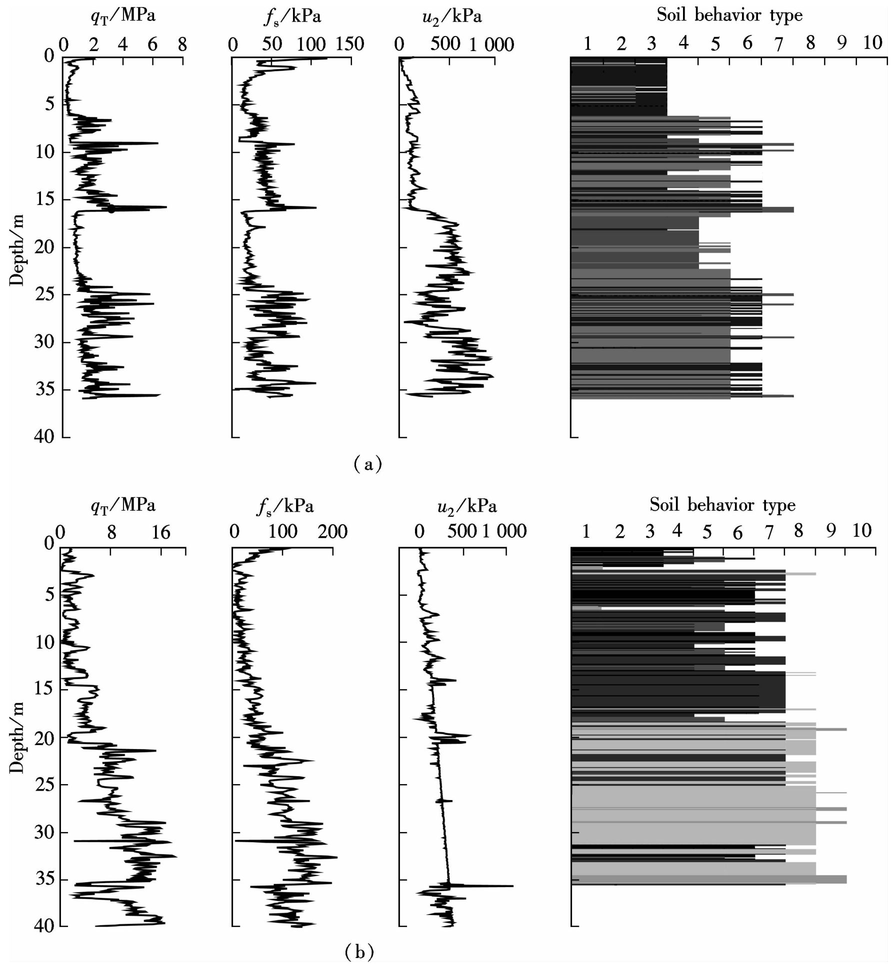
The seismic piezocone penetration device used in this study is produced by Vertek-Hogentogler & Co., USA. The equipment is a versatile piezocone system equipped with advanced digital cone penetrometers fitted with 60° tapered and 10 cm^2 tip area, 150 cm^2 sleeve surface area cones. The system can provide measurements of five independent readings: tip resistance q_T, sleeve friction f_s, penetration porewater pressures (shoulder u_2), vertical inclination with depth and down-hole shear wave velocity V_s, which is recorded at 1 m intervals during the pause of rod connecting. It is particularly important in piezocone tests that pore pressure dissipation tests be performed in steady state in situ conditions at specific depths during a pause following one sounding, yielding information about the coefficient of consolidation and the permeability of a soil deposit. In order to have a good pore pressure response during piezocone penetration, a rigid procedure to assemble and saturate the piezocone system[8] is employed. Fig. 2 shows the typical profiles of piezocone tests at the study sites.

2 Results and Discussion

Of particular note is that existing theories for S_u interpretation from CPTu data involve several simplifications and assumptions. Therefore, existing correlations must be "calibrated" against high quality laboratory test data. In this paper, at the site of the Fourth Nanjing Yangtze River Bridge, the site-specific correlations for clayey soils are developed based on comparisons of predicted and laboratory measured profiles of S_u. Because the S_u value is always affected by many factors, such as the initial stress state, the direction of loading, the rate, stress history, degree of fissuring, boundary conditions, and so on, the interrelationships and calibrations are required to connect all the various laboratory strength modes to the individual in-situ piezocone tests.

Fig. 3(a) shows the values of S_u with depths obtained from the above tests. As indicated by the potential trends, UU tends to produce lower values of S_u with little scattering than DSS and CDS. Such lower and more varied values of S_u from laboratory test results are common in engineering practice, mainly because of disturbance caused by sampling, other experimental procedures and partially drained shearing processes when using samples with high silt content. Based on the laboratory tests, values of N_{kt}, N_{ke} and $N_{\Delta u}$ at site A, are evaluated using S_u references obtained from three different modes of shearing and q_T from CPTu performed adjacent to each borehole. A wide range of these values can be seen in Figs. 3 (b), (c) and (d). These significant scatterings in the results may be attributed to three possible sources of uncertainty in the tests, including different laboratory shear modes, disturbance of sampling and following procedures, and uncertainty of CPTu measurements (q_T, u_2). Of particular note is that the variations of floodplain sediment environments may be mainly responsible for the variations. Moreover, the sampling depths may incidentally not correspond with the CPTu testing depths, which results in exceptional data points.

Taking DSS as the reference values, N_{kt} values vary from 7 to 24, as shown in Fig. 3(b), and the majority of N_{kt} values is in the range of 8 to 15 with an average value of 11.6, which is lower than those expected on the basis of previous recommendations. The resulting N_{kt} profile on the basis of CDS tests has trends nearly identical to the aforementioned profile, but with somewhat lower values and more scattering.



3—Clay; 4—Silty clay to clay; 5—Clayey silt to silty clay; 6—Sandy silt to clayey silt; 7—Silty sand to sandy silt; 8—Sand to silty sand; 9—Sand

Fig. 2 Typical results of piezocone tests and corresponding soil types. (a) Site A; (b) Site B

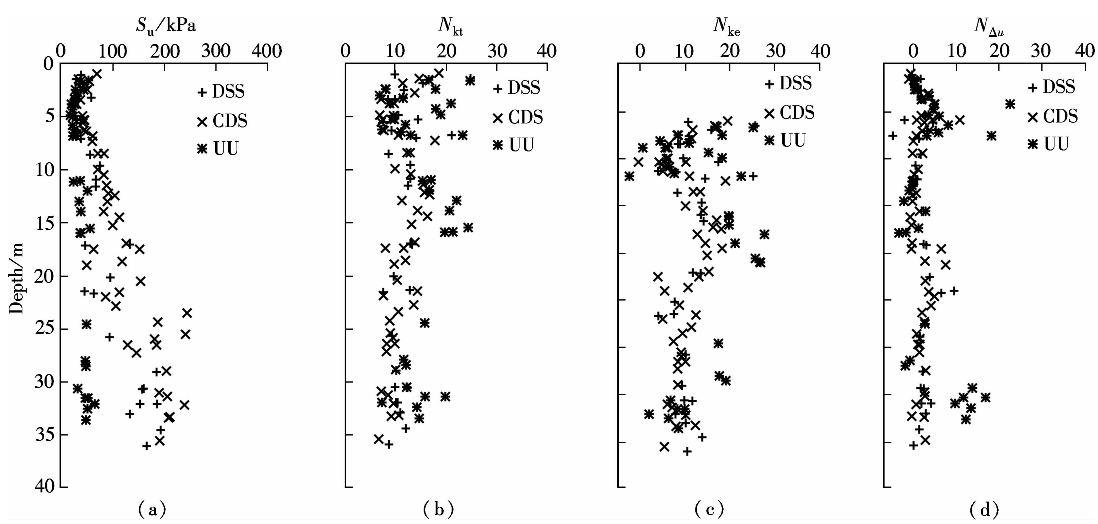


Fig. 3 Depth profiles of S_u, N_{kt}, N_{ke} and $N_{\Delta u}$ from various shear strength tests. (a) S_u; (b) N_{kt}; (c) N_{ke}; (d) $N_{\Delta u}$

The corresponding values of N_{kt} are from 7 to 18 with an average value of 11 and most of the data varies between 7 and 16. Fig. 3(b) also shows that values of N_{kt} based on UU tests are greater than those based on DSS and CDS tests. Fig. 3(c) shows N_{ke} obtained by different shear mode tests. The values are also scattered significantly. Moreover, some negative values or very small values are observed because the u_2 measurements are larger than (or close to) the q_T measurements at certain locations. Therefore, small errors in q_T or u_2 measurements become sensitive. The major disadvantage of S_u interpretation using q_e in this project is evident[8]. If all the abnormal points are ignored, the average values of N_{ke} based on DSS, CDS and UU tests are 11.5, 10.8, 15.7, respectively, similar to the values presented by Lunne et al[8, 11]. Except for some negative or very small values of $N_{\Delta u}$ shown in Fig. 3(d), the overall trends are relatively better than those illustrated in Figs. 3(b) and (c). The average values based on DSS, CDS and UU tests are 2, 2.4, 7, respectively. However, due to the uncertainty of porewater pressure measurements, the complexity of soil types and testing procedures (such as porewater element saturation problems), this method seems not always encouraging to geo-engineers, especially at the highly stratified sites like the Yangtze River floodplain sites.

For sites A and B described in this paper, the N_{kt} value based on CDS is recommended for the S_u prediction at similar sites, because the values of S_u obtained from such tests have been widely used in foundation design in China. Fig. 4 presents measured values from CDS tests and calculated values of S_u at site B using the N_{kt} value (=11) obtained from site A. Reasonable matches with variations mostly within ±30% are observed, which implies that the CPTu-based method for S_u evaluation is feasible. Additional verification based on more subtle anisotropic consolidated undrained compression (CAUC) tests, used as main references by many researchers[8], is suggested in order to apply the method to other sites for the absence of such tests in this study.

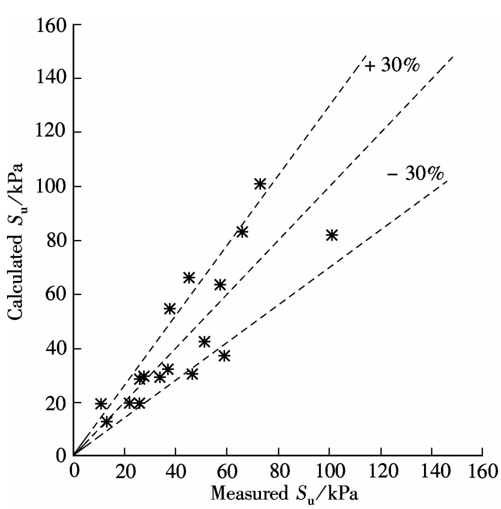


Fig. 4 Measured values of S_u vs. calculated values for verification Site B using N_{kt} method

3 Conclusions

The CPTu is a widely accepted tool in western countries. However, the CPTu is seldom used in China due to various reasons. In this study, several series of the CPTu data are collected at two bridge anchorage sites in Nanjing, China. Analysis is conducted to evaluate the performance of three different CPTu-based methods to determine S_u values. The results show that:

1) For clayey soils, the values of the cone factor, N_{kt}, N_{ke} and $N_{\Delta u}$, depend on the test type used to obtain a reference S_u, and on sample disturbances.

2) Overall, N_{ke} shows more scattering than N_{kt} and $N_{\Delta u}$. For the highly stratified and layered nature of the sediments, it is recommended using the net cone resistance q_T to estimate S_u and the preliminary cone factor values N_{kt} are from 7 to 16, with an average of 11 if taking the CDS strength as the reference value. When the u_2 measurements are reliable, using the excess pore pressure to estimate S_u seems more reliable, especially, for very soft clay, where q_T measurements may be uncertain.

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桥梁基础工程中基于 CPTu 的粘性土不排水抗剪强度确定方法

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摘要：为了给南京长江四桥基础工程设计与分析提供可靠的长江漫滩粘性土不排水抗剪强度 S_u 参数，采用国外引进的孔压静力触探（CPTu）测试系统进行了现场原位试验，并以高质量土样的室内试验作为参考，对几种基于 CPTu 的 S_u 确定方法进行了对比与评价，同时对所提出的圆锥系数 N_k 值进行了验证. 试验结果表明：圆锥系数 N_{kt}，N_{ke}，$N_{\Delta u}$的大小取决于剪切试验模式及试验扰动程度；N_{ke}一般比 N_{kt}，$N_{\Delta u}$表现出更大的离散性；对于长江漫滩多夹层粘土地基，建议采用净锥尖阻力 q_t 预测 S_u，相应的圆锥系数 N_{kt}数值在 7 ~ 16 之间，平均值为 11；应用 CPTu 新技术，可以为桥梁基础工程设计提供合理的设计参数.

关键词：不排水抗剪强度；孔压静力触探；粘性土；圆锥系数；桥梁基础

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