A comparative study of international CPTU and China double bridge CPT tests

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ABSTRACT: The cone penetration test (CPT) and piezocone penetration test (CPTU) with the measurement of pore pressure are some of the more powerful site investigation tools especially for soft clay. Most of the correlations with geotechnical data were developed based on 10 cm^2 international CPT and CPTU results, but in China there are 15 cm^2 and 20 cm^2 CPT devices. Firstly, the difference between the Chinese CPT and the international modern multifunctional digital CPTU techniques are compared. Results are presented comparing various sizes and configurations of China double bridge CPT and CPTU in Jiangsu clays of China. According to the CPT and CPTU tests at five sites, parameters measured by the 10 cm^2 CPTU are presented and compared to China double bridge 15 cm^2 CPT. The findings provide added confidence to use the 10 cm^2 international CPTU in engineering practice in China.

1 INTRODUCTION

The Cone Penetration Test (CPT) and in particular the Cone Penetration Test with measurement of pore water pressure (CPTU) commonly referred to as the “piezocone test” are widely used for geotechnical and geo-environmental site investigations. However one must have confidence in the results being obtained. During the gathering of data it was found that in China the most commonly used CPT devices are the single bridge CPT and the double bridge CPT, and the cone size was either 10, 15, or 20 cm^2 cones and not the 10 cm^2 device more commonly used elsewhere in the world. The 10 and 15 cm^2 refer to the cross sectional area, A_c, in Figure 1; the cones also having different friction sleeve areas, A_s.

The International Reference Test Procedure for the CPT/CPTU (IRTP, 1999) only deals with the 10 cm^2 cones but allows for variation in x-sectional area: 5 cm^2 to 20 cm^2. For example, a larger piezocone is more robust and, depending on the load cell arrangement and specification, can give more accurate cone resistance data in soft soils; a smaller one can give better detection of thin layers, via the pore pressure response (Lunne et al. 1997; Tumay et al. 2001).

When different sizes of CPT and CPTU are employed, the question of scale effects inevitably arises. For piezocones ranging in area from 5 to 15 cm^2, the usual assumption, based on experience summarized by Lunne et al. (1997), is that scale effects are negligible in soil layers of sufficient thickness relative to the cone diameter: that is, quantities such as the cone resistance and excess pore pressure do not depend on the size of the piezocone. However, in highly interbedded soils, significant scale effects are to be expected. This issue was studied theoretically by Vreugdenhil et al. (1994) for cone resistance, and a scale effect on pore pressure was demonstrated experimentally by Hird et al. (2003), who compared the results from 1 cm^2 and 5 cm^2 piezocones in specially constructed soil models. Powell and Lunne (2005) compared the results using the 10 cm^2 and 15 cm^2 piezocones in UK clays. Hird and Springman (2006) presented the comparative performance of 5 cm^2 and 10 cm^2 piezocones in a lacustrine clay.

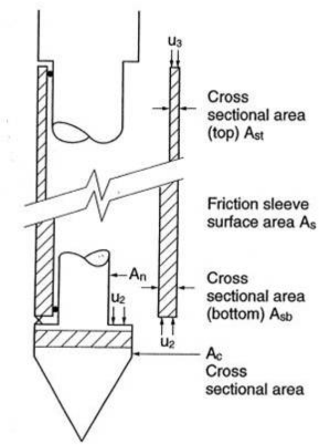


Figure 1. Section through piezocone showing pore pressure effects on measured parameters (after Lunne et al. 1997)

Most of the correlations developed for the CPT and CPTU are based on the results from 10 cm^2 test equipment. It is known that many factors can affect the results of CPT tests if care is not taken in the specification of the equipment and testing, however little has been reported on the effects of size of device, both diameter and area of friction sleeve, on the measured results. Based on the difference between the Chinese CPT and the international modern multifunctional digital CPTU, this paper summarizes the testing results undertaken with 10 cm^2 modern CPTU and 15 cm^2 double bridge CPT devices in well documented Jiangsu clay test sites. The findings should give added confidence to the use of 10 cm^2 modern piezocone penetrometers in geotechnical engineering practice.

2 COMPARISONS BETWEEN CHINA CPT AND INTERNATIONAL CPTU

Since the development of the original CPT in about 1932 in Holland, the CPT has now established its position as a routine, reliable, and expedient means for geotechnical site investigation. Experiences about CPT operation and application have been largely accumulated. Many literatures and manuals have been published. Research on CPT continues to have high priority in USA and Europe since the origin of CPT. CPT in China before the late 1980's had reached the same development level as that in Western countries. However, in the years following, the theory research and the application practice of CPT in China have been markedly lagging compared with western developed countries.

2.1 Comparison of CPT probe standards

During the period of the early 1960's ~ the late 1970's, the international communication between China and western countries was few in geotechnical engineering. As for the development of CPT, the different technical standards and specifications were established in China, including the equipment, testing procedures and data interpretations (Liu and Wu 2004). At present stage, the single bridge CPT is only used in China. Although the double bridge CPT is developing gradually in China, its technical standards are different from the international CPT standards, see Table 1.

2.2 Comparisons of application and its reliability

The use of CPT establishes an excellent site investigation practice, with no disturbance when compared with traditional boring methods like auger drilling, and others. So the CPT technology is developing internationally and innovating rapidly since its origin. However, due to the different probe standards and the lagging sensor technologies in China, the interpretation of CPT data is different and its reliability is low. The reliability and precision of modern CPTU and its derivatives is much higher than Chinese single or double bridge CPT.

Detailed comparisons on the applications between China and the western countries are as follows:

2.2.1 Soil classification

Table 1 shows the different measured parameters of Chinese CPT and multi-functional CPTU. The single bridge CPT measures only one parameter, specific penetration resistance (p_s) which includes cone tip resistance and sleeve friction. The double bridge CPT can measure two parameters, q_c and f_s. In China, most of the classification charts have been related to q_c, f_s and friction ratio, $R_f = (f_s/q_c)$•100%. The measurements of modern CPTU include corrected cone resistance, q_t , f_s and u. Several classification charts have been developed using q_t, R_f and B_q, [$B_q=(u-u_o)/(q_t-\sigma_{vo})$], u_o = static water pressure, σ_{vo} = total overburden stress (Robertson et al. 1986; Robertson 1990). As mentioned above, the classification scheme used in China is less accurate and reliable than that of western countries. Especially, the modern multi-functional CPTU system can provide a large amount of information in real time during a single penetration, integrated with inclination-, seismic-, resistivity-, and other modules.

Table 1. Measured parameters of modern CPTU and Chinese CPT (Liu, 2004)

CPT Type	p_s (MPa)	q_c (MPa)	f_s (kPa)	u (kPa)	Resistivity (Ω•m)	V_s (m/s)	Temperature
Chinese single bridge CPT	√	×	×	×	×	×	×
Chinese double bridge CPT	×	√	√	×	×	×	×
Multi-functional CPTU	×	√ (q_t)	√	√	√	√	√

(Note: √-available, ×-not available)

2.2.2 Soil profile

Compared to the single and double bridge CPT in China, the ability of the modern CPTU to distinguish between sands and clays is more accurate, especially if dissipation tests at specific test depths are done. Due to the sensitivity of 5 mm porous element and continuous profile, the thin sand layer among soft clay or the thin soft layer among sands can be detected accurately. While the borings often ignore these thin layers, which is sometimes important to foundation design.

2.2.3 Soil engineering parameters

Except for the parameters measured by the single and double bridge CPT, the measurements of the modern CPTU and its derivative parameters have been diversified. Flow and consolidation properties are not obtained by the single and double bridge CPT tests. However, these parameters are useful for settlement computing of soft clay foundation as well as the improvement schemes design.

3 GROUND CONDITIONS

The test sites are located in the Jiangsu province, which geologic element comprises the Quaternary deposits. These Quaternary deposits are located in Nanjing, Lianyungang, Changzhou, Suzhou and Taizhou city respectively (Figure 2). The Quaternary deposits are backswamp, marine, alluvial and lacustrine, including clay, silty clay, silt and silty sand. Results have been gathered from five well documented test bed clay sites and data from these will be presented in this paper to illustrate the findings in the following soil types;1 slightly overconsolidated marine clay, 2 moderately overconsolidated alluvial and lacustrine clays and 3 normally overconsolidated backswamp clays. Details of their basic properties are given in Table 2.

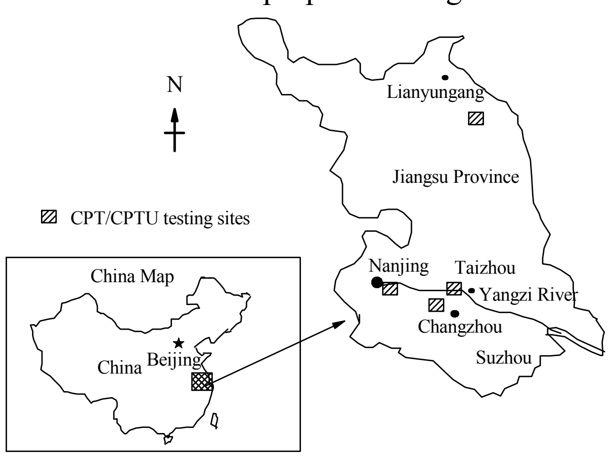


Figure 2. Location of the five CPT/CPTU test sites

4 PIEZOCONE PENETROMETER EQUIPMENT

The specifications of the available China double bridge CPT and modern CPTU cones, are given in Table 3. The modern CPTU piezocone used in this study had shoulder filters for pore water pressure measurements (u_2). The cones were calibrated over the range of loads likely to be encountered on the sites.

Table 2. Soil properties of the clay sites

Sites	w (%)	w_p (%)	w_L (%)	I_p	e	γ (kN/m^3)
Jinling library	41-43	20-22	37-39	16-17	1.187-1.206	17.3-17.8
Lianyan expressway	74-76	37-39	63-65	23-25	1.992-2.116	15.3-16.6
Ningchang expressway	23-25	19-22	38-39	17-18	0.603-0.733	19.4-19.9
Husuzhe expressway	53-54	21-23	41-43	18-20	1.005-2.093	15.3-18.5
Taizhou	37-39	18-20	30-32	12-13	1.056-1.185	17.6-17.8

Table 3. Details of CPT/CPTU used

Cone type	Apex angle (°)	Cross sectional area-cone (cm^2)	Surface area of friction sleeve (cm^2)	Area ratio a
Modern CPTU	60	10	150	0.80
China CPT	60	15	300	-

The baseline tests were performed using a 10 cm^2 single-element Hogentogler electronic cone with an interchangeable tip (Hogentogler & Co., Columbia, Md.), capable of measuring u_2 pore water pressures. The vertical force on the end of the cone was measured with a load cell of 100 kN capacity. The combined force on the end of the cone and on a friction sleeve of area 150 cm^2 was similarly measured, and the force on the friction sleeve was calculated by subtraction. The China cone was connected to 10 cm^2 driving rods by a tapered connector. Note that modern electronic cones provide the signal conditioning and amplification of data downhole within the penetrometer, whereas electric (China) cones require amplification of the signals by the data acquisition system at the ground surface.

It is well established that pore water pressures in the ground generated as a result of the cone penetration influence the measured results (Lunne at al. 1997; Cai et al. 2006). Due to the "inner" geometry of a cone penetrometer the ambient pore water pressure will act on the shoulder area behind the cone and on the ends of the friction sleeve, as shown on Figure 1. For the cone resistance the unequal area is represented by the cone area ratio "a" which is approximately equal to the ratio of the cross-sectional area of the load cell or shaft, A_n, divided by the projected area of the cone A_c as shown in Figure1. The corrected total cone resistance is given by the equation:

$$q_t = q_c + u_2(1-a) \qquad (1)$$

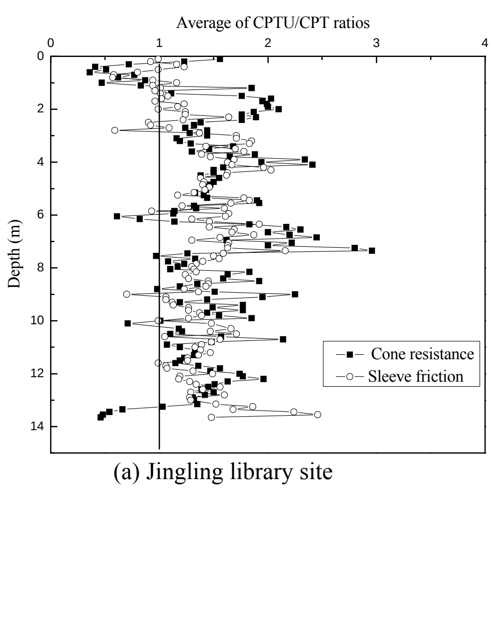
where u_2 = pore pressure acting behind the cone. The determination of the cone area ratio "a" is best made by the use of a simple calibration vessel and not by idealized geometrical considerations (Lunne et al. 1997). It has been shown that when applying the correction to q_c consistent results can be obtained in terms of the corrected cone resistance q_t when comparing a variety of 10 cm^2 cones with different internal geometries (Lunne et al. 1997).

5 EXPERIMENTAL RESULTS

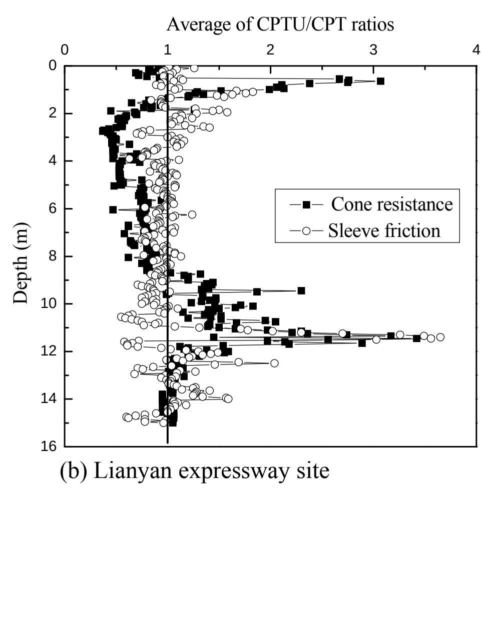
The CPT measures 2 parameters, namely the cone resistance (q_c) and the sleeve friction (f_s). While the CPTU measures 3 parameters, which are the cone resistance (q_c), the sleeve friction (f_s) and the pore pressure (u). It has been usual to present these measurements as profiles plus the friction ratio ($R_f = f_s/q_c$ expressed as a percentage). As a result of the foregoing discussion all measured cone resistances were corrected for pore water pressure effects but the sleeve frictions were left uncorrected as u_3 was not measured. The CPT and CPTU tests were carried out at 28 locations. Typical spacing between adjacent CPT and CPTU was 2 m for reducing the soil variability. The elevations of the ground surface at different sites were measured and the difference in elevation considered.

To quantify the differences between CPT and CPTU measurements, the ratios of the CPTU to CPT cone resistance (q_c or q_t) and sleeve friction measurements were calculated for each site. The depth increment of 10 mm was used and the data were averaged over the depth interval before calculating the ratio. The ratios with depth are shown in Figure 3 for the five sites, respectively. The reference line positioned at a CPTU to CPT ratio equal to one in the plots of average ratios represents the theoretical value if soil variability was eliminated and if there was no effect of cone size. In general, the ratios of cone resistance and sleeve friction measurements fluctuate near one, and the measured values increase with depth. For each increment, the mean and coefficient of variation of the q_c (or q_t) and f_s CPTU to CPT ratios were calculated. The average CPTU to CPT q_c ratios are in range of 0.75-1.25, while the average f_s ratios range from 0.87 to 1.53. The coefficient of variation for CPTU/CPT ratios ranges from 8% to 28%. The coefficient of variation of the f_s ratios is on average 25% larger than the q_c ratios. Further insight into the factors that affect both the q_c and f_s ratio values is obtained when the soil profiles are distinguished. It should be mentioned that the tendency of variation is dependent on the soil types. For the soft clay sites (Figure 3b and d), the average ratio of the friction sleeve is always significantly greater than the average q_c ratio. For the topsoil such as fill and silty clay, the ratios CPTU to CPT fluctuate drastically.

Both the q_c and f_s ratios contain some horizontal variability. However, soil variability is not the sole source of the large increase observed in the f_s measurement, since the f_s ratios are much larger than the q_c ratios. If soil variability was the only cause for the ratios to be greater than one, the ratios of q_c and f_s would be similar (if not equal).



(a) Jingling library site



(b) Lianyan expressway site

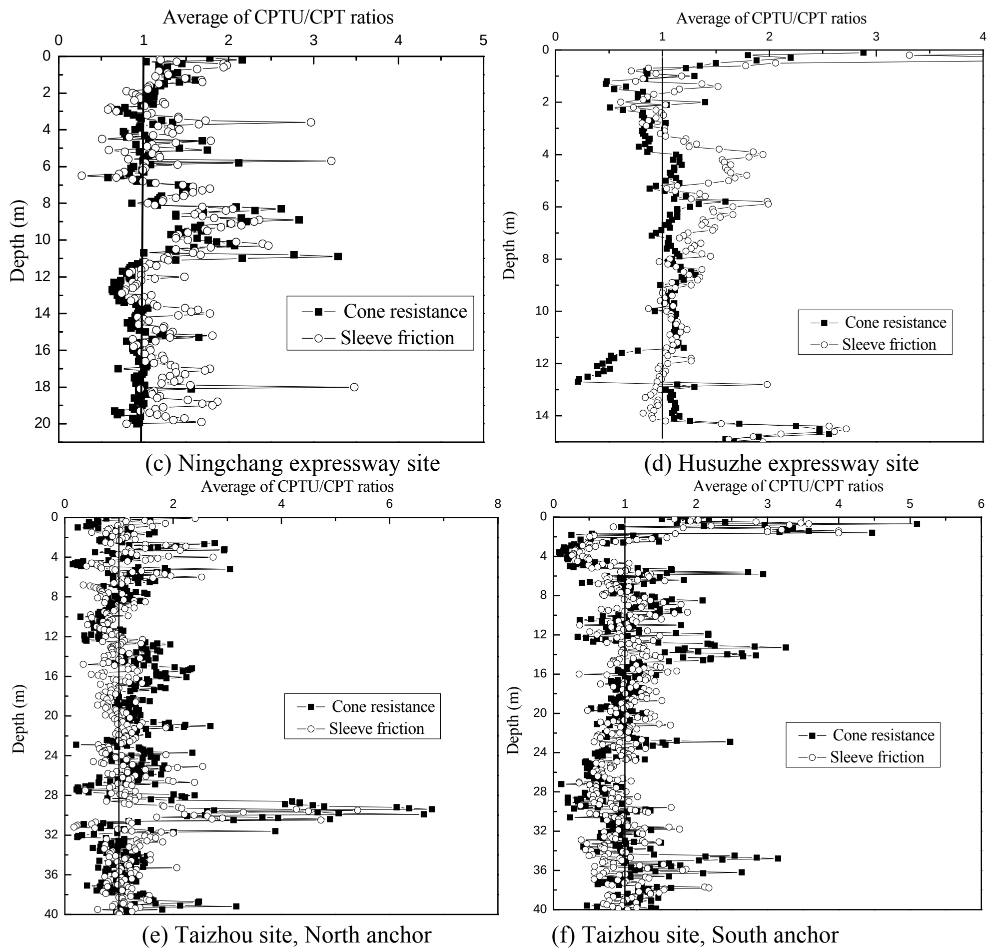


Figure 3. Statistical analysis of q_c and f_s ratios at the five sites

6 CONCLUSIONS

Firstly, the difference between the Chinese CPT and international modern CPTU techniques are compared. The comparison includes the different standards, specifications, measurement functions and their reliability. CPT and CPTU soundings performed at the five Quaternary clay deposits sites in Jiangsu province of China have provided valuable information on the penetration resistance and pore-water pressure behavior observed in different soils. The CPT and CPTU soundings and dissipation tests were completed using two different penetrometers including two sizes (10 and 15 cm^2) equipped with shoulder u_2 filter elements.

Measured cone resistance is a function of individual cone inner geometry. Corrected cone resistance appears unaffected by cone size when pore water pressure effects are taken into account. Measured sleeve friction would appear to be very similar for two cones and, within a general scatter band, implying it to be independent of sleeve diameter and sleeve area. However in soft soils the inaccuracies may mask end area effects. It appears that there is little difference between 150 and 300 cm^2 friction sleeves on cone penetrometers. Most consistent parameter especially in soft soil is the pore water measurements provided good saturation is achieved and maintained. Provided care is taken in calibration and cone set up then results from 10 and 15 cm^2 cones are generally comparable in clay soils.

The general implications for engineering practice are that correlations based on 10 cm^2 piezocones can be used with the same confidence for 15 cm^2 China double bridge cones. The information available with regard to 15 cm^2 cones will be significant in concluding the debate on size of friction sleeves when standardization of the 15 cm^2 devices is completed.

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