Influence of rate of penetration on CPT tip resistance in standard CPT and in CPTWD (CPT while drilling)

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ABSTRACT: Sometimes performing the CPT with standard penetrometer is not possible; in these cases it is possible to use a wireline rotary drill-rig equipped with CPTWD (Cone Penetration Test While Drilling) but often the tests are carried out at significantly low rate of penetration (RoP). Comparative tests with different RoPs between standard CPT and CPTWD have been performed to evaluate the influence of both method of pushing and RoP. A tentative correlation between qc and the RoP is suggested. CPT results to a depth of 30m using CPTWD at a slow RoP are presented at a site where the standard CPT could not be carried out due to stiff soils. The interpretation of CPT results with “unconventional” ways of pushing the cone into the soil (e.g. CPTWD) involve a challenge to derive geotechnical parameters for a wider range of soil types compared to “standard” CPT.

1 INTRODUCTION

Cone Penetration Testing (CPT) as a general way of getting data by penetrating the soil with a cone has become a “standard” because the geometry of the cones is standardised as well as the way of pushing and the rate of penetration (RoP). At present there are several different types of cones, measuring additional parameters but the basic rule for CPT defines that the RoP should be constant around 2 cm/s (+/- 10%), meaning that to get correct data according to the standard the RoP should range from 1.8 to 2.2 cm/s. For example the RoP can decrease: when pushing into dense or stiff layers; when the reaction of the pushing system is insufficient to provide a stable reaction; when the penetrometer is oscillating (i.e. operating from the top of a non-heave-compensated-barge); when the pushing is done with non-standard methods, for example CPTWD (Cone Penetration Test While Drilling).

2 CPTWD (Cone Penetration Test While Drilling)

The CPTWD (Cone Penetration Test While Drilling) system is an integration between a standard CPTU and a wireline coring system; sometimes the MWD (monitoring while drilling) recording is also added, so as to have a matrix with all the CPTU parameters and the MWD parameters (Flow, Torque, thrust, Rop, etc) all together versus depth every 2 cm. The CPTWD also allows to alternate CPTU strokes with sampling, coring, and down-the-hole testing. Also at the end of the test, since the hole is always cased with rods whose inner diameter is 107 mm, there is the possibility to install almost any geotechnical instrumentation (piezometers, extensometers, inclinometers, etc.).
In summary the system is made up of:

• Drilling rods (or "casing") inside which a “core barrel” can be latched.

• Core barrel or drilling tool: this is placed inside and it is lowered/lifted by a cable/wire (wireline): the corebarrel is designed in order to make the cone protrude up to 50 cm beyond the drill bit, to recover it when the total thrust on the cone exceeds its max. capability, and to create a calibrated flush of mud around the upper part of the cone-rod for lifting drill-cuttings up

• standard or special CPTU cone mounted in the special corebarrel and protruding 50 cm

To date, the CPTWD has always been used with standard drill rigs, having a nominal thrust ranging from 8 to 12 tons and not balanced, in the sense that the point of application of the thrust was not close to the center of gravity of the rig. In addition there is not always the possibility to keep a constant RoP while varying the thrust in drill rigs. The execution of the CPTWD test has to be made while searching for the right balance between thrust and water/mud flushing in order to make the cone penetrate at a reasonably constant RoP close to the standard without making the drill-string get stuck. For the abovementioned reasons sometimes the CPTU strokes in CPTWD tests were not performed at a constant RoP and sometimes not at the standard RoP, very often significantly slower.

However, in general, the results of the CPTWD always appeared to be good and, when comparison with standard CPTU was possible, the two show very good agreement when the results are superimposed (Sacchetto et al., 2004).

The biggest challenge for making a significant comparison between CPTWD and standard CPTU is that to carry out deep CPTU tests it is necessary to deploy a powerful penetrometer and a drill rig for making preholes once the penetrometer reaches its limit; therefore statistically we do not have a significant numbers of tests made with both methods in a wide range of comparable soil types.

A CPTWD test (see Figure 1) was performed in a site where the stratigraphy is unusual: from 0 to 13 m sandy gravel, and from 10-12 m to 160 m very dense silt, sometimes more or less sandy or clayey, but apparently uniform based on visual observation of the cores. In that site, after a pre-hole 13.4 m deep and anchoring the drill-rig to increase the reaction force, we were unable to push with both the standard CPTU and the Marchetti’ dilatometer (DMT). Then we tried with CPTWD with extremely low RoP, and we were able to get continuous data from 17 to 30.5 m and we could have tested deeper.
The results of the CPTWD shown in Figure 1 show that the $q_c$ is very high, constantly over 25 MPa, as well as the $f_s$; the $u$ ($u_2$ position) appears to sense the percentage of clay/sand in the silt. This CPTWD test was carried out about 10 m from a continuous core borehole with samples and in situ (SPT, pressiometer) testing. However, the borehole results are currently not yet available. The CPTWD results appear to capture the correct stratigraphy.

3. COMPARATIVE TESTS

3.1 Standard CPTU

Three series of CPTU were carried out with the following equipment and procedures:

- Standard cone penetrometers, 200 kN and 300 kN rigs anchored with 2 or 4 augers; digital piezocone with measurement of $q_c$, $f_s$, $u$, inclination and RoP every 2 cm.

- Execution of a CPTU at the standard RoP = 19.6 – 20.0 mm/s; execution of a second CPTU at RoP = 15 mm/s (medium); execution of a third CPTU at RoP = 7.4-10 mm/s (slow). Each CPTU was spaced no more than 70 cm apart.
These comparison tests were carried out at three sites (around 50-80 km distance one from the other) where the soil profiles are typical of the shallow sediments of Padana Valley: i.e. alternate thin layers of clayey silt or NC silty clay and sandy silt with several sand layers. At all the sites there are sometimes very thin layers of organic clay or overconsolidated clay.

For each site the CPTU results were superimposable and showed no significant difference between the $q_c$ values. An example comparison from one site is shown in Figure 2. In order to consider the soil stratigraphy changes (although tests were very close one each other) all the $q_c$ values to be compared in the 2 non-standard-RoP-tests have been “bandpass” filtered, setting apart all the values lower than 80% and higher than 110% of $q_c$ at the standard RoP and keeping the others as comparable. Different bandwidths have been set in filtering $q_c$ values since the differences in the layers were not negligible in spite of the proximity of the tests.

The ratio between $q_c$ at different RoP and the standard rate of 20 mm/s have been calculated: i.e. $q_{c15}/q_{c20}$ and $q_{c7.4}/q_{c20}$ for RoP of 15 and 7.4 mm/s, respectively. The average ratios were also calculated along the whole depth, firstly not distinguishing soil type (i.e. clay, sand, silt) and then repeated only in specific layers: sand and clay (not counting mixed layers, or very interlayered strata).

An average ratio for the fully profile was found for the three sites: $q_{c(x)/q_{c(standard)}} = 0.879 \approx 0.931$ depending on the site.

Repeating the analysis in either clays or sands (see Figure 3):

$q_{c(x)/q_{c(standard)}} = 0.931 \approx 0.954$ and in sands:

$q_{c(x)/q_{c(standard)}} = 0.831 \approx 0.892$

The comparison of sleeve friction ($f_s$) values at different RoP was not feasible, because the soil had too many layers, and the tests were slightly different. The superimposed $u$ profiles did not show a significant variation. It would appear that the penetration pore pressure ($u$) values are more affected by other factors (stratigraphy, saturation) than by the RoP. In general decreasing the RoP the profile of $u$ became less detailed, and the variations passing from clay to sands or viceversa are less fast (i.e. the reaction of the pore pressure is slower). The same general behaviour was observed in deep CPTWD tests carried out at low RoP, but not having any standard CPTU to compare with. Figure 3 shows that the trend of decreasing of $q_{c(x)/q_{c(standard)}}$ is more or less linear with the decreasing of the RoP, but there is a difference between clays and sands. The slope of the line for sands is more steep. It would appear that, at these sites, the penetration resistance in sand is more sensitive to RoP.
Fig. 2 $q_c$ profiles of standard CPTU executed at different Rates of penetration (CPTU 19.6: $\text{Rop}=19.6$ mm/s; CPTU 7.4: $\text{Rop}=7.4$ mm/s; CPTU 15.1 $\text{Rop}=15.1$ mm/s)

Comparison #1 between $q_c$ values (MPa) at different RoP
3.2 CPTWD

There are few tests in which a statistically significant comparison can be made between “standard” CPTU and “special” CPTWD for deep penetration. CPTWD results can also be affected by the method of pushing, because in CPTWD the total protruding length outside the drill bit is no more than 50 cm, so it could have been difficult to split the influence of “method” from that of the RoP. Figure 4 presents a comparison between a CPTWD and a standard CPTU in terms of measured tip resistance $q_c$. The scale of the plot has been enhanced in order to point out the differences. During this CPTWD test the RoP was on average in a range from 1.0 to 1.5 cm/s in cohesive soils and around 0.8 to 1.0 cm/s in sands (sometimes less); the same cone penetrometer was also used for both tests. The tests were made in a site located on the delta of the River Po, with “normal-consolidated” silty clay down to 31 m and then alternating clay and sand to the maximum reached depth of 120 m.

Similar to the results presented in Figure 3, there is a general slight decrease of $q_c$ in CPTWD compared to $q_c$ in CPTU. The sleeve friction ($F_s$) and penetration pore pressure ($u$) did not show a significant variation. The differences in $q_c$ could be given by the different method of pushing and some by the natural variation of the soil, especially in sands (the 2 tests were made 20 m far from each other).
Fig. 4: Superimposition of $q_c$ in CPTWD (in red) and CPTU (in blue) tests – the scale of $q_c$ is enhanced.

Figure 5 shows a CPTWD test carried out in the same site (delta of Po River). Included in Figure 5 is the variation in RoP versus depth, together with $q_c$, $f_u$, $u$. The RoP varies between 6 to 18 mm/s, in average around 12 mm/s.

Fig. 5 Example CPTWD profile at site in Po River Delta including Rate of Penetration.
4 CONCLUSIONS

There are basically two main differences between CPTWD and standard CPTU: the way the cone is pushed into the soil (the “method”) and the Rate of Penetration (RoP). In order to better understand the different contributions due to “method” and RoP, comparisons were made between standard CPTU and CPTWD and results of shallow tests made with standard CPTU but at different RoPs. In both cases (deep and shallow) the results confirm the expectations: \( q_c \) decreases proportionally to the decreasing of RoP, \( f_s \) and \( u \) do not seem to be significantly affected by RoP. The variations of \( u \) appear to depend more on other factors, like saturation and/or the natural variation of the soil (very interlayered in all the shallow tests). The few comparative deep tests (CPTU vs. CPTWD) show the same trend. Therefore, the slight difference in \( q_c \) (especially in clays) can likely be attributable to the RoP, and not to the “method” and nor to the depth. On the other hand performing tests with non-standard methods and non-standard RoPs in “non-penetrable” soils and/or to much deeper depths opens a wider scenario.

Once ascertained that CPTWD (as a “method” of pushing) contributes to the possible variations of data mostly due to variations in the RoP, the requirements for using CPTU data obtained by this non-standard method in a correct way would be to at least: (a) determine correlations between RoP, \( q_c \), \( f_s \), \( u \) based on a much wider number of tests (shallow and deep) run in different types of more uniform soils; (b) the data should also be confirmed with other kind of tests; (c) assess and compare the field data with those coming from advanced mathematical models; (d) once found a valid correlation between CPTU parameters and RoP improve the interpretation software not only considering \( q_c \), \( f_s \), \( u \) vs. depth for calculating geotechnical parameters, but also Rate Of Penetration.

It has to be pointed out that the evaluation of the geotechnical parameters (such as \( c_u \), \( \varnothing \), etc) made with the usual correlations and the usual softwares is normally more affected by several other factors than the slight variation of \( q_c \), \( f_s \), \( u \) with a slower RoP than standard. Therefore, it could be useful for the engineers to know also the RoP for eventually correcting the parameters according to different Rates of Penetration.

REFERENCES