Comparing in-situ cone resistance and pile jacking force

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ABSTRACT: Pile jacking is a relatively recent piling technique, characterized by low vibrations during execution, small size installation equipment and good axial bearing capacity performance. These features make it a viable alternative to traditional dynamic pile driving, particularly for historical buildings and urban sites. The prediction of the short-term resistance encountered during installation, generally different from the medium-term bearing capacity, is important in any application of the technique. For this purpose, a correlation between the short-term jacked pile installation force and the CPT tip resistance will improve the prediction reliability. Data from a well documented field study in Italy are reported, in which a number of jacked piles were installed and their short-term base resistance recorded. The subsoil is composed of a predominantly clayey and silty fraction with local sandy layers. Data analysis is provided and comparison with previous studies and CPT-based design methods discussed.

1 INTRODUCTION

1.1 *Background*

Cone penetration testing (CPT) has recently gained importance in pile design, due to both the reduction of the cost of such investigations and the need for more precise and accurate estimations of the bearing capacity of piles. The growing interest in constructing on-shore and, above all, off-shore pile installations has prompted several design codes to adopt new and more refined CPT-based design methods. Even the most recent version of API RP2A (2007) has accepted four modern techniques based on CPT (UWA-05, NGI-05, ICP-05, Fugro-05), replacing the traditional approach based on plasticity theory. Among the existing types of piles a relatively new one, known as jacked or pressed-in piles, is becoming more widely used. Jacked piles combine a high bearing capacity and stiffness, even higher than driven piles (Deeks *et al.*, 2005; Yetginer *et al.*, 2006), with low levels of noise and vibration during installation (White *et al.,* 2002), which makes them particularly suitable for urban applications. However, the fact that existing design methods are, at least partly, calibrated on data coming from dynamically installed piles, requires designers to pay particular attention. The possibility of getting accurate records of the installation resistance, through instruments applied to the hydraulic jacks, gives the designers additional information for evaluating the pile behaviour. Recent studies on driven closed-ended piles based on load-test data (White & Bolton, 2005) suggest that, taking into account the correct reduction factors, the ultimate unit base capacity q_b and the cone tip resistance q_t assume very similar values – i.e. q_b/q_t = 0.9 - confirming the analogy between piles and penetrometer behaviour. Considering jacked piles, which are driven into the soil by a pseudo-static force in the same way as the penetrometer, the analogy is even more consistent and, therefore, similar values for q_b and q_t are expected. However, studies carried out on base installation resistance q_b of jacked piles in sandy and silty soils (Jackson, 2007; Jackson *et al.*, 2008) have shown that the q_b values can be significantly lower (approximately $\alpha = q_b/q_t = 0.35$ for sands and 0.45 for silts). These results are assumed to be related to the effect of different degree of partial drainage during penetration in such soils. In this paper a particular type of jacked pile, known as Soles® pile, is investigated and installation data discussed. The base resistance records q_b have been analysed and compared with q_t values. The prediction of the short-term resistance encountered during installation, generally different from the medium-term bearing capacity, plays a major role in efficient project design.

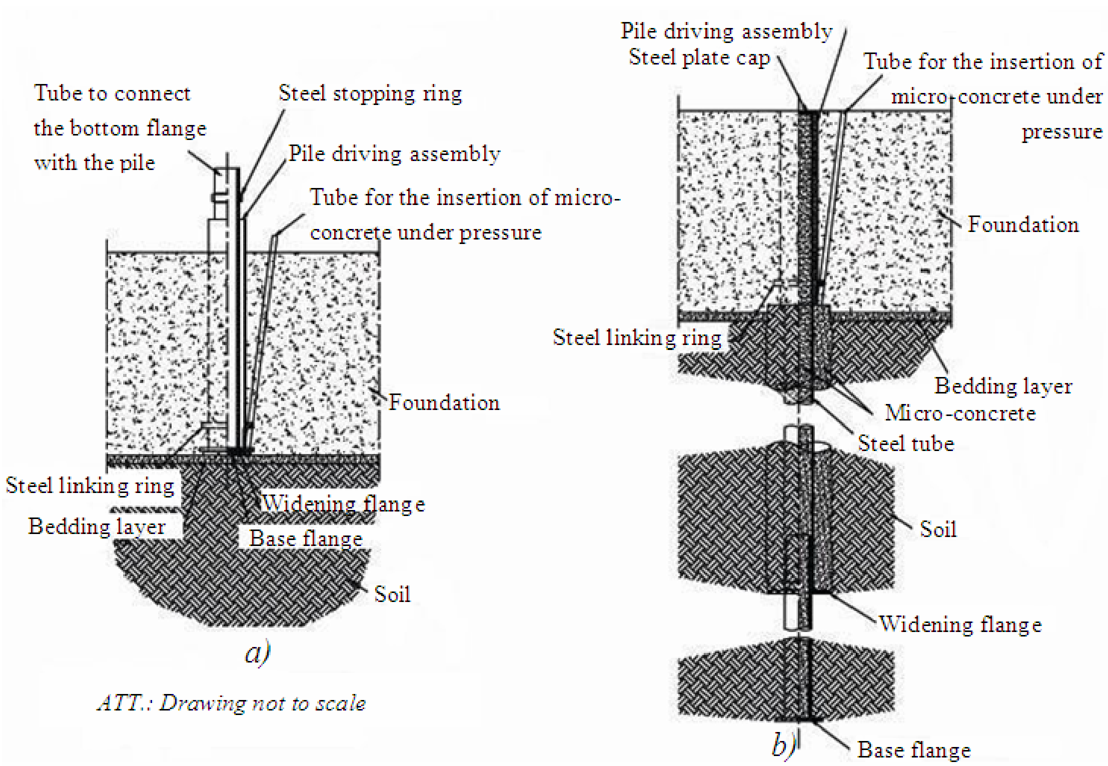

Figure 1. Pile schematic sections: *(a)* detail of foundation with pile installation assemblies; *(b)* pile driving operations.

1.2 *The jacked piling technique*

The Soles® pile (Figure 1) is a specific type of jacked pile, installed by means of special hydraulic jacks (Figure 2) and cast in-situ. This relatively new piling technique offers many advantages over traditional dynamic pile driving. In particular, the low level of noise and vibration produced during installation make the use of this pile particularly suitable for applications in historical buildings and urban sites. In addition, the small size installation equipment can be easily handled in restricted spaces. The schematic section of Figure 1 shows the main pile components. The pile steel hollow tube (Figure 1b) is driven into the ground via a static jacking force applied by hydraulic jacks (Figure 2). The foundation raft serves as counterweight and creates a connection between piles and superstructure by means of the driving assembly, previously positioned inside the concrete foundation. The pile base is closed by two flanges, a base flange and a widening flange. During installation, the flanges create an annular space between pile and soil which is filled with micro-concrete, maintained under pressure during installation. Consequently, the pile-soil contact surface is quite rugged and the shaft resistance improved. At the end of the installation process, the inner part of the pile is filled with concrete.

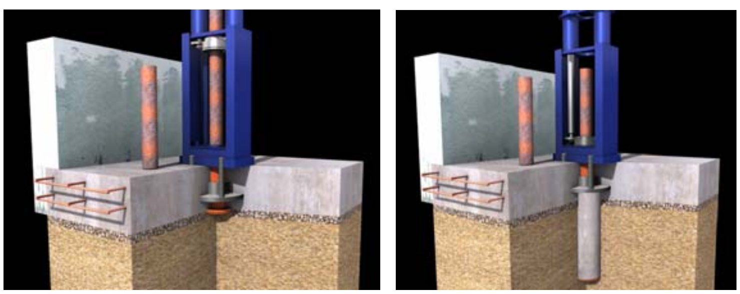
Figure 2. Pile installation process.

2 A CASE STUDY

2.1 *Installation and test methodology*

Data herein presented and discussed come from a site in Forlì (Italy), where 43 piles (lay-out in Figure 3) were installed in February 2008 at a penetration rate v≈20 mm/s. The diameter of the widening flange was D=450 mm. The pile installation was part of a major intervention of raising a traditional farmhouse (see the view of the building in Figure 4), in order to reach the current roadway and to create extra height for a basement below the existing structure. The building was jacked vertically upwards, using an electronically controlled system to keep the whole structure in plane during lifting - a technique developed by the company to move buildings intact. The old structure was prepared for jacking by construction of a new mat in which driving assemblies were positioned and piles installed. The unit base resistance q_b of 12 piles was automatically recorded by calibrated pressure cells. Note that, due to the fluid lateral micro-concrete, the shaft resistance during installation is negligible.

2.2 *Foundation soil profile*

A geotechnical site investigation was carried out, which mainly consisted of one continuous coring borehole and six piezocone tests (see Figure 3); in addition, a number of dissipation tests in low permeability soils were performed and several undisturbed soil samples extracted for the subsequent laboratory tests. A schematic section of the relevant subsoil, together with four testing logs, are shown in Figure 4.

The soil profile underlying the building consists of three distinct soil units:

- Unit A: alternating layers of silty clay and clayey silt;
- Unit B: silty sand;
- Unit C: sandy gravel.

The CPT results (Figure 4 and Figure 5) indicate that the strata in the area are laterally inhomogeneous - the sandy layer (unit B) thickness being locally variable. This problem has major repercussions on data analysis, as discussed in the next section. The pile bases rest on the lower gravelly bed (Unit C), approximately at 28 m depth.

3 RESULTS AND ANALYSIS

Figure 5 shows all CPT tip resistance data (Figure 5a) and the unit base resistance q_b (Figure 5b) recorded during installation of all the 12 instrumented piles. As observed, since during jacking the external micro-concrete is still liquid, the shaft friction is negligible. Thus, the force applied by hydraulic jacks at the pile head is practically equal to the base resistance Q_b developed during installation. For conventional closed-ended piles the unit base resistance q_b is calculated dividing the total base resistance Q_b by the sur-

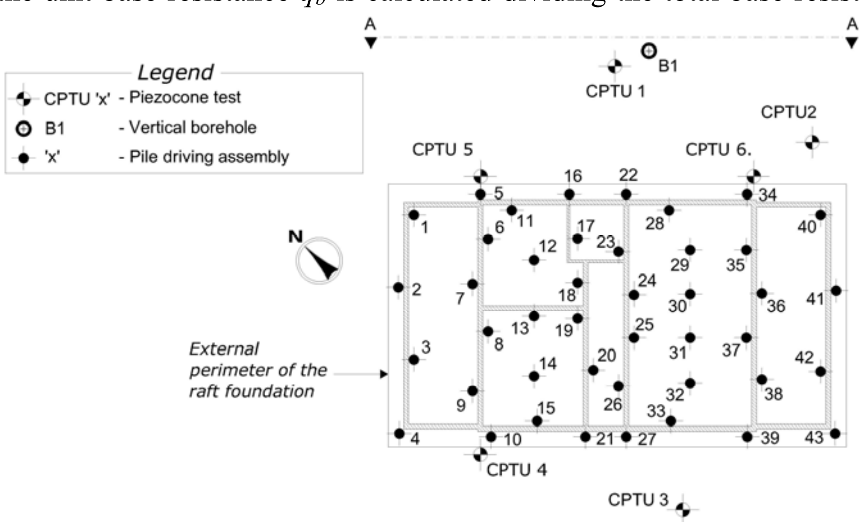

Figure 3. Plan of the building with piles lay-out and location of geotechnical investigations.

face area of the tip. The pile tip in this case is a structure made of two flanges separated by a steel tubular section (Figure 1b), so the way of calculating q_b deserves some attention: a specific study has been carried out to understand how the tip shape affects the base resistance during installation and it turned out that double flange piles require a jacking force approximately ten per cent higher than single flange piles, the difference, almost constant for variable piles and depths, being possibly related to the development of some lateral friction along the shaft between the two flanges, where liquid concrete is missing. However, further investigation is needed for the full understanding of the phenomenon. Here, the unit base resistance q_b was calculated by dividing the jacking force Q_b by the surface area of the widening flange, as a circular shape; this method should provide acceptable results for the purpose of this study, although q_b might be slightly overestimated. Comparing Figures 5a and 5b, the correspondence between pile jacking force and piezocone tip resistance is clearly visible, due both to the similar geometry and to the application of a pseudo-static installation force. The q_b curves are much smoother than CPT logs, not only because the instruments used to record the jacking force of the piles are less accurate than CPT equipment but, above all, because of the different scale

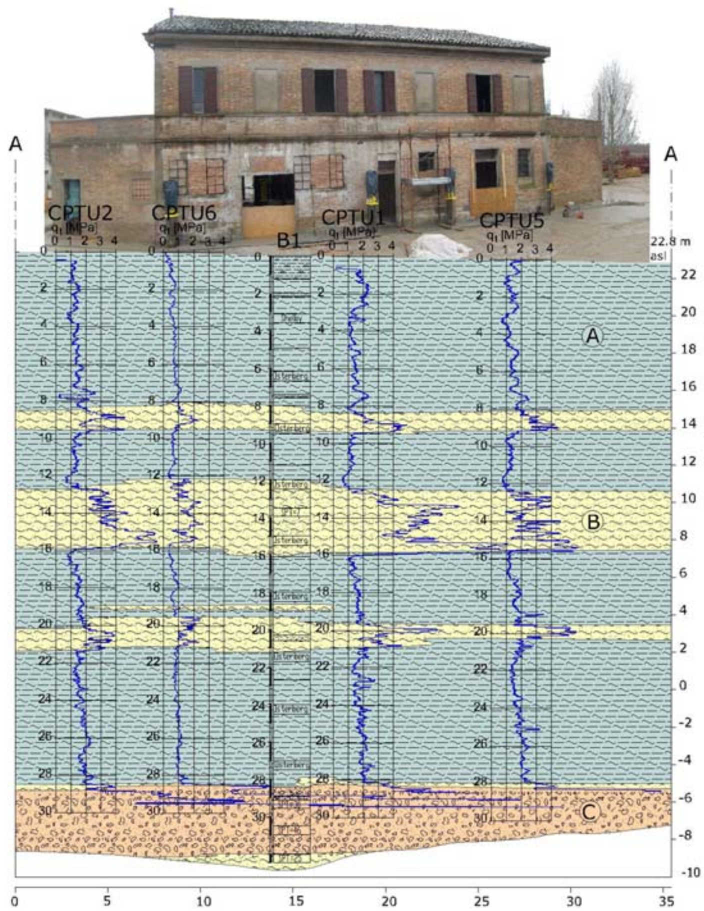

Figure 4. Schematic section (A-A in Figure 3) of the subsoil, from the in-situ testing logs and view of the building.

effect induced by the significant diameter size difference between cone and piles, when penetrating soil layers of variable thickness; therefore, the presence of thin layers barely affects the unit base resistance curves. Considering the q_b curves in the depth ranges where the soil is laterally homogeneous (Figure 5b), the piles show a rather consistent and repeatable behaviour. For a reliable analysis to be developed, attention was focused on the three following layers: a first silty clay layer, from 4 to 8 m below ground level, a second sandy layer from 14 to 17 m and a third silty layer from 25 to 28 m. As shown by CPT logs (Figure 4), the sandy layer (Unit B) must be handled with care, because of its variable thickness within the site and of the diffused silty lens. In Figure 6 the ratio between q_b and q_t ($\alpha = q_b/q_t$) is plotted for such three homogeneous layers, with q_t from the most representative CPT 2 only. The mean values of the ratio for each section is plotted with a solid red line. The other dashed lines show the results of previous relevant studies and design methods; note that two of them (White and Bolton, 2005 and UWA-05) are related to medium-term behaviour, as they were obtained from pile load test databases. A more relevant comparison can be made with the work by Jackson (2007), who analysed closed-ended jacked piles. Figure 6 shows for this study the strong dependence of

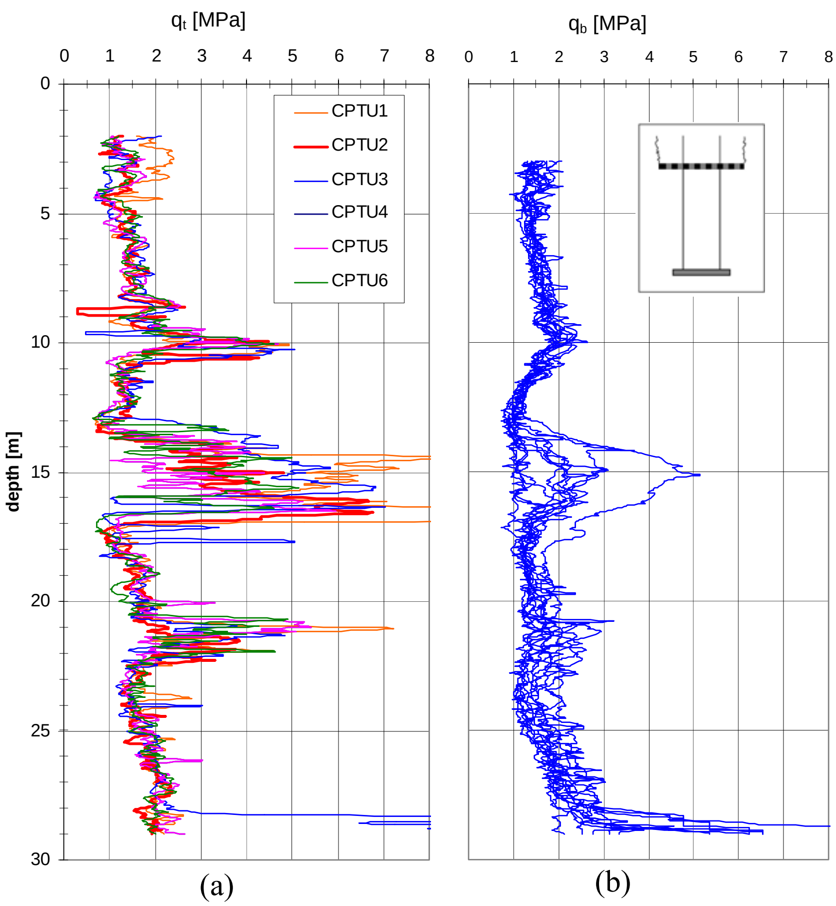

Figure 5. *(a)* CPT tip resistance data and *(b)* records of jacking force during pile installation.

the q_b/q_t ratio on the grain size confirming Jackson's trend: the finer the soil, the higher the ratio. Nevertheless, average values here are typically higher: 0.5 for sand, 1 for silt and 1.1 for silty clay. Such values for the sand layer, confirm the importance of partial drainage effects (Jackson *et al*., 2008): variable degrees of drainage, in fact, differently affect the tip resistance of devices of variable size, when penetrating soil layers of intermediate behaviour. In particular, ratios obtained in silt tend to unity (i.e an ideal value, usually not reached even for medium-term capacity), as both cone and piles tend to the same undrained regime. For this specific type of pile, in case of silty clay the ratio reaches values consistently greater than one and in other sites, where piles have been jacked in pure clay, values up to 1.3 have been obtained. The fact that q_b is slightly overestimated by the presence of the double flange can partly give reason of the results, but a better understanding of the relative importance of partial drainage during penetration and of its implications in the correct estimate of the parameter $\alpha = q_b/q_t$ requires further investigation, from fully drained to fully undrained conditions, suitably expressed by the dimensionless normalized velocity vD/c_h.

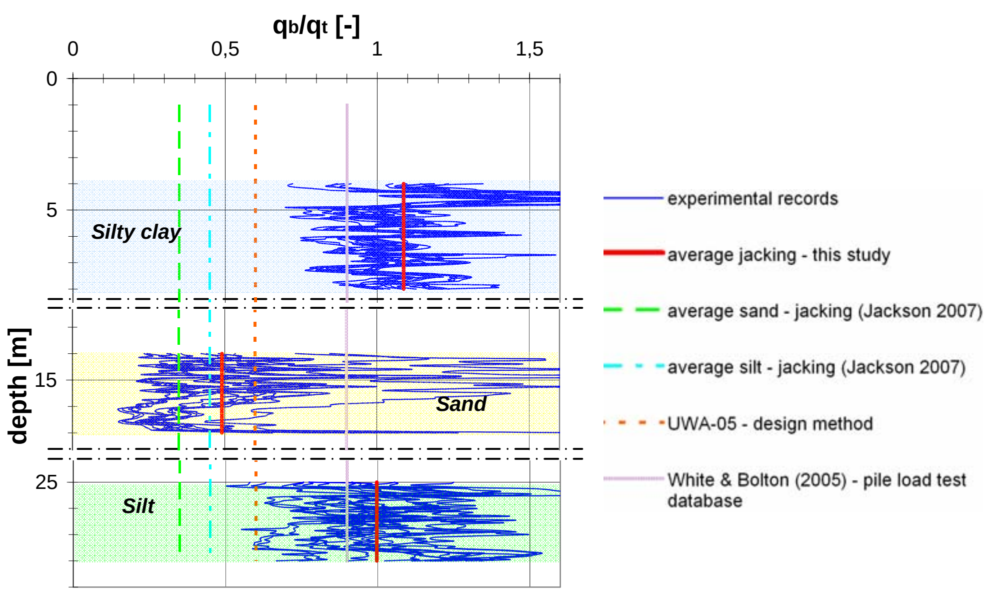

Figure 6. Comparison between this case and previous studies.

4 CONCLUSIONS

An extensive field test, carried out near Forlì (Italy) with the aim of comparing the short-term jacked pile installation force and the CPT tip resistance, has been presented in the paper. For this purpose, a number of piles were installed and 6 CPT tests performed. A rather innovative pile jacking technique and devices for recording relevant data have been described. The close analogy between CPT and jacked piles installation processes has been discussed, thus confirming that modern pile design methods based on CPT parameters are especially suitable for predicting their long-term performance. The specific case study was selected among other reported test sites, both for the quality of available data and for the presence of different natural soils, i.e. predominantly clayey and silty fractions with local sandy layers. The investigated test site shows a ratio between the jacked pile installation force and the CPT tip resistance rather consistent with the few reported data in the literature and strongly dependent on the soil type. In particular, in silty sand layers, variable degrees of partial drainage during penetration are likely to occur on devices of different size, providing a ratio considerably less than unity. On the other hand, in finer layers, such ratio tends to increase and become even higher than one. Data analysis has been shown and comparison with previous studies discussed. CPT data appear to provide a better understanding of the jacking mechanisms and hence enable to predict the short-term resistance that will be encountered during installation.

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