Application of CPT for adequate selection of pile driving techniques

I.B. Ryzhkov
BashNIIstroy, BGAU, Ufa, Russia
O.N. Isaev,
NIIOSP, Moscow, Russia

ABSTRACT. It is proposed to apply CPT data for evaluating pile driveability to specified depth on the basis of available soil data, pile strength and hammer capacity in order to prevent pile damage and underdriving and to ensure adequate piling operations efficiency. Pile driving problems are reviewed in the case of high-strength soils and large-size boulder occurrence. Known dependencies are used that relate pile resistance to set per blow (“refusals”), through which the number of blows is determined. Unification criteria for pile driving depth are proposed to exclude underdriving and trimming of underdriven pile heads.

1 INTRODUCTION

Practical application of footings on driven piles has demonstrated that, in spite of correct pile bearing capacity evaluation, the assigned footing effectiveness is not guaranteed without detailed elaboration of pile driving technology. During construction operations there may occur situations when piles do not reach the design depth and/or are damaged during driving that result in contingent delays and possible updates of the project design.

The Russia’s standards (СП-50-102-2003), as well as those of other nations, relate pile hammer capacity to the pile design load with the allowance for some additional factors. Such approach does not fully reflect specific conditions of pile footing application. The design pile load does not always characterize the problems of driving process. If a bearing bed occurs at several meters depth and is overlaid by soft soils, then usually neither powerful hammers nor shock-resistant piles are required. On the contrary, in hard clay soils pile driving to design depth can encounter difficult problems even in the case of moderate pile loads (500…600 kN). The case of pile driving in hard soils are quite frequent, especially when the upper layers feature stiff soils, but unfit to bear shallow footings (collapsible loess soils, loess-like soils, expansible soils, etc.), which are to be “pierced through” by piles.

Extensive experience of driven piles application in Russia demonstrates that underdriving issues are facilitated if CPTs are used to reveal soil stratification peculiarities at many points of the surveyed site.
2 EVALUATION OF PILE DRIVEABILITY INTO HARD SOILS

The method, discussed below, is based on compliance with the following two requirements:
- pile hammers shall ensure both the possibility of driving piles to predefined depth and the required duration of such driving process (the design operations efficiency);
- pile strength shall exclude their damage in the course of driving.

Compliance with these two requirements is based on prediction of the number of hammer blows to drive a pile to the specified depth. This number enables evaluation of both the pile driving duration and the required shock resistance of such pile.

CPT helps determine pile limit resistances \( F_{u,j} \) within the whole interval of its “intermediate” driving depths \( (h_j = 1, 2, 3 \ldots h, m) \), through which it “passes” during driving before it reaches the design depth \( h \). At the next stage of analysis these values of \( F_{u,j} \) become input data for predicting the estimated set per blow at these (“intermediate”) depths for a particular hammer. Known “dynamic” equations are applied, which interrelate pile limit resistances with set (with the account of specific features of piles, hammers, damping pads in pile helmet, etc.). Thereafter, the computed pile set \( s_a \) are used as inputs for estimating the hammer blows number, and the set inverse value is the number of blows per unit length (driving depth). Such computations are performed for each meter of driving depth, and the set is defined in terms of meters, as follows:

\[ n_i = 1/s_a,i \]  

(1)

with \( s_a,i \) as estimated mean set per blow in the \( i \)-th meter of driving; \( n_i \) as estimated number of blows in the \( i \)-th meter of driving (from depth \( h_{i-1} \) to \( h_i \)).

Summation of hammer blows number for each meter of driving \( n_i \) \((i = 1, 2, 3, \ldots h)\) yields the unknown number of blows \( N \), required for pile driving to the whole depth \( h \) in question

\[ N = \sum_{i=1}^{i=h} n_i \]  

(2)

The calculations are performed with the help of respective computer code (there is computer code “INVESTIGATION” in BashNIstroy). Accuracy of the obtained results follows from the applied dynamic equation “\( s_a \sim F_u \)” and correctness of the hammer blow actual energy (bounce height of diesel hammer depends on soil strength). Fig. 1 shows typical comparison of actual and calculated numbers of hammer blows in the course of pile driving process (prismatic concrete piles 9 m long, delluvial hard plastic and hard clay loams, tubular hammer with 1250 kg striking ram). Dependence of set per blow on pile resistance was assumed as per “Gersevanov equation”, given in the above-mentioned Russian code CII 50-102-2003.

For large-scale construction projects (10..12 m long piles) a hammer option shall ensure 5…10 minutes rate per one pile driving. Most diesel-hammers blow frequency is usually 50…60 min\(^{-1}\) i.e., the allowable \( N_t \) shall correspond to the range of 250…600 blows.
In order to comply with the second requirement it is necessary to know the allowable number of hammer blows, $N_{ult}$, which is not detrimental to piles. Detailed information about it was obtained by G.F. Novozhilov (1987), who carried out a great many experiments of pile “durability”, including destruction of hundreds of concrete piles. There were obtained empirical relationships, connecting the value of $N_{ult}$ with the design and strength of driven piles, and a pile impact strength classification was proposed. Piles with steel-fiber concrete head feature the highest impact resistance, steel-fiber-concrete being concrete reinforced with steel fibers i.e., thin steel fiber pieces (usually wire). Lateral reinforcement and use of claydite concrete also ensures BashNIIstroy diagrams for concrete piles (10-15 m long), most typical for Russian construction applications.

![Figure 1. Examples of calculated diesel-hammer blow counts ($N_c$) with actual ones counted during pile driving ($N_f$); points, related to the same pile are connected with lines at its different driving depths (Yenikeev, 1990)]](image-url)
Table 1. Numbers of blows, non-destructive for concrete piles with tubular hammer, having 1.8 t striking ram

<table>
<thead>
<tr>
<th>Pile type</th>
<th>Type and thickness of pad</th>
<th>Min. compression resistance of concrete *, MPa, (class of concrete)</th>
<th>Blow counts, causing cracks</th>
<th>Total pile head destruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piles with lateral reinforcement and prestressed axial reinforcement</td>
<td>oak ( s=0.15 \text{ m} )</td>
<td>20 (B20)</td>
<td>&lt;50</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>oak ( s = 0.2 \text{ m} )</td>
<td>25 (B25)</td>
<td>150</td>
<td>270</td>
</tr>
<tr>
<td>Pile with lateral reinforcement and non-prestressed axial reinforcement</td>
<td>oak ( s=0.15 \text{ m} )</td>
<td>20 (B20)</td>
<td>&lt;50</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>oak ( s = 0.2 \text{ m} )</td>
<td>25 (B25)</td>
<td>200</td>
<td>370</td>
</tr>
<tr>
<td>Idem with steel-fiber-concrete head with 1% reinforcement</td>
<td>oak ( s=0.15 \text{ m} )</td>
<td>20 (B20)</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>oak ( s = 0.2 \text{ m} )</td>
<td>25 (B25)</td>
<td>1200</td>
<td>2000</td>
</tr>
</tbody>
</table>

* Minimum strength of standard cube 15×15×15 cm

3 APPLICATION OF PILES IN BOULDER GROUNDS

Occurrence of large boulders is typical for some moraine grounds and marine deposits. Angular blocks occur in elluvial soils. These soils are usually rather compacted, thus providing high bearing capacity for driven piles, therefore, pile footings could be highly cost-effective in such conditions. Nevertheless, a great number of boulders may restrict application of pile footings because of the risk of many piles to be underdriven. A pile, sitting on a boulder, does not always possesses the required bearing capacity, it is especially so if pile encounters a boulder at a shallow depth. This is why design of footings in such soils always requires prediction of the share of piles, which would not reach the design depth due to collision with boulders. Such problem can be successfully solved with the help of static penetration tests (CPT), as the number of points, at which the site could be tested, would be much greater than the number of piles.

Admissibility or inadmissibility of the expected underdriving rate (and pile trimming rate respectively) depends on site conditions. Nevertheless, in most cases, as is shown by experience, underdriving (trimming) shall not exceed 5…8 % of the total volume of the project.

The boulder size, capable of stopping a pile or a cone probe, depends on many factors (strength of soil under boulder, pile dimensions, power of hammer, cone penetration resistance, etc.). Nevertheless the research, done by the authors, showed
that the dimensions of a boulder, capable of “stopping” a cone probe, are times 2…3 less than those of a boulder, capable of “stopping a pile (having 0.3×0.3…0.4×0.4 m). In most typical cases (e.g., a cone pushed down with 100 kN force into stiff clay loam at 5…8 m depth) a 0.3×0.4 m dia boulder will stop a cone. The pile of above dimensions could only be “stopped” by a 0.8…1.0 m boulder. In harder soils at greater depths the boulder sizes in both cases would be slightly less.

Thus, cone penetration “failures” within the same site should happen more frequently than pile underdrivings. However, in order to quantify the percentage of points, at which a cone probe would not reach the assigned depth, in terms of the expected percentage of pile underdrivings, the fractional composition of stone inclusions should be known.

Approximate data about the volume and fractional composition of boulders could be borrowed from the available local operational and site survey experience. The evaluation procedure is facilitated provided a geometrical feature of two-phase media is taken into account. As is well known, the “bulk” porosity (the share of pores in a volume), the “plane” porosity (the share of pores in an arbitrary cross section) and the “linear” porosity (the share of line segments, belonging to pores, along an arbitrary line, crossing the porous media) are roughly equal. It’s so-called “Akker-Cavalieri principle” (Babkov & Polak 1965). This principle can be attributed to the medium, in which instead of pores there occur solid alien inclusions (boulders in the discussed case). Assume that distribution of boulders in soil massif is random, then the boulders, revealed on the bottom and in the walls of an excavation, would prompt a rough estimate of the boulder share in the soil massif as well as their fractional composition. The following value plays a special role:

\[
K_{\text{pile/cone}} = \frac{V_{D>D_{c,pile}}}{V_{D>D_{c,cone}}},
\]

with \(V_{D>D_{k,pile}}\) as volume of boulders, irresistible for piles (i.e., having the diameter, exceeding a certain “critical” value \(D_{c,pile}\)); \(V_{D>D_{k,cone}}\) as volume of boulders irresistible for cone (i.e., having diameter, exceeding a certain “critical” value \(D_{c,cone}\)).

Fig. 2 shows the curves, obtained by calculating dependence of the share of cone penetration “failure” points (i.e., the points, where the cone could not reach the assigned depth due to collision with a boulder) versus the share of piles, underdriven because of boulders. The calculations were based on the assumption that the share of boulders of a certain size (e.g. \(V_{D>D_{k,pile}}\) in the volume of soil \(V\ i.e.,\ V_{D>D_{k,pile}}/V\) was defined as probability of such boulder occurrence in an arbitrary point of the soil massif in question. Probability of a cone or a pile encounter with a boulder in this massif was defined as probability of occurrence of “at least one boulder” on the cone or pile path, whose size would be greater than the critical one (i.e., \(D_{c,cone}\) for cone and \(D_{c,pile}\) for pile).

As is seen on Fig. 2, the less would differ boulder critical dimensions for piles \((D_{c,pile})\) and for cone probe \((D_{k,cone})\) the less would differ percentages of pile underdrivings and “failed” cone penetration points. Minor difference between \(D_{c,pile}\) and \(D_{c,cone}\) is characteristic of predominance of large-size boulder fractions i.e., in soils, containing large-size boulders, the share of underdriven piles should not differ much from the share of “failed” cone penetration points. On contrary, predominance of
small-size boulders gives rise to the great difference. Fig. 2 shows that the admissible 5…8% of pile underdrivings could correspond to 55% of “failed” cone penetration points (with $K_{pile/cone}=0.1$).

Notably, easier practical situations may occur, when adequate decisions require neither calculation nor auxiliary graphs e.g., the absence of cone collisions with boulders within the site prompts that the boulders are non-existent or they are so few that their presence is negligible. On the contrary, if boulders were encountered at all cone penetration points than pile option should be abandoned.
4 PILE LENGTH DEFINITION IN DIFFICULT DRIVING CONDITIONS

The design lengths and number of piles in hard soils should be selected in combination with their driving technology. It stems from the fact that feasibility of piling operations is not solely related to hammer and pile strength parameters. Sometimes it is economically feasible to prevent underdriving of piles by reducing their length and increasing their number. This is evident from the two cases of pile driving with the help of the same hammer when erecting a footing bearing the same load $N_o$ (Fig. 3). On Fig. 3a piles are driven to “zero” set per blow (“zero” refusal), therefore, their driving depths differ (as result of soil heterogeneity). Pile length has to be assigned as per points with softer soils, otherwise, the design (“zero”) set per blow could not be reached. As all $n$ piles have identical “zero” set, their bearing capacity should be identical i.e., corresponding to the maximum value for the given hammer capacity.

Fig. 3b shows piles, driven by the above hammer, but to equal depths, corresponding to minimal depth on Fig. 3a. The refusals would be greater than those on Fig. 3a, and would differ for different piles. Mean pile resistance (bearing capacity) on Fig. 3b would be lower than that on Fig. 3a, therefore, in order to bear load $N_o$ for the option on Fig. 3b greater number of piles would be required ($\Delta n$ piles more). But no pile trimming is required for option on Fig. 3b, which is unavoidable for option on Fig. 3a.

Fig. 3 shows that the volume of concrete would be less in the option, in which the sum of shaded portions would be less (i.e., those of “underdriven” pieces on Fig. 3a, and those of “additional” piles on Fig. 3b). It is evident that if the total volume of “additional” piles (Fig. 3b) is twice as great as that of “underdriven” piles than option 3a (driving to specified refusal) would feature lower material consumption, and visa versa.

Research, carried out by BashNIIstroj, showed that the growth of pile resistance with depth is essential. If 1 m greater (or less) depth increases (or lowers respective-
ly) pile bearing capacity by less than 90…100 kN than option on Fig.3b would consume less material (pile driving “to assigned depth”). Otherwise, if pile bearing capacity strongly grows versus depth (as is the case of pronounced “bearing bed”) the pile footing on Fig.3a, driven to “given refusal” would be more economical.

Solution of all these issues requires the data on pile resistance dependence on depth at many points on the site that could be easily obtained with the help of CPT procedure.

CONCLUSION
The CPT method is a convenient tool to solve a number of the following engineering problems, pertaining to erection of footings on driven piles:
- Evaluation of pile driveability with the help of available equipment;
- Timely rejection of a piling option in the case of numerous large-size boulders occurrence;
- Materials optimization of footings with the account of expected underdriven piles trimming.

REFERENCES


Еникеев В.М. Исследование и разработка методов зондирования просадочных грунтов для проектирования свайных фундаментов. Дис. …канд. техн. наук. – Днепропетровск, 1980.


Babkov V.V. & Polak A.F. (1965) About the geometry of the pore space / Proceeding of BashNIIsstroj. Vol. IV. Moscow: Strojisdat