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Research Paper

Pile driving formulas based on pile wave equation analyses

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ABSTRACT

Pile driving formulas, which directly relate the pile set resulting from a hammer blow to the static load capacity of the pile, are often used to decide whether a pile will have the required design capacity. However, existing formulas do not consider soil or pile type, and do not, in general, reliably predict pile capacity. In this paper, an advanced model for dynamic pile driving analysis was used to develop accurate pile driving formulas. The proposed driving formulas are validated through well-documented case histories. Comparisons of predictions from the proposed formulas with results from static and dynamic load tests show that they produce reasonably accurate predictions of pile capacity based on pile set observations.

1. Introduction

Proper modeling of pile driving is important for both planning and inspection of pile driving operations. The dynamic response of a pile during driving is very complex, involving the interactions of the hammer, cushion, pile and soil during application of an impact load. Because the pile driving process is variable and imposes significant changes to the state of the soil around the pile that are difficult to model, both the design and quality control of piling operations have been subject to considerable uncertainty and have been approached conservatively [1].

Reliable estimation of the capacity of a driven pile based on the ease or difficulty with which the pile is driven allows an inspector to decide when pile driving can be discontinued. One of the tools that may be used to decide whether an installed pile will have the predicted capacity are pile driving formulas, which relate the pile set per blow to the capacity of the pile. Due to their simplicity, these formulas have been widely and frequently used in practice. Most follow the rational derivation of dynamic pile capacity using impulse-momentum principles to empirically relate the energy generated by the driving system to the pile displacement. They differ depending on simplifying assumptions and empirical adjustments. Moreover, existing pile driving formulas make no distinction of the soil type surrounding the pile (e.g., clay or sand) or the pile type (end-bearing versus floating or friction piles). As a result, the formulas used in practice often either largely over-predict or under-predict capacity [2]. Safety factors as large as six have been recommended when using these formulas [3].

Existing pile driving formulas are based on a simple concept: the energy of the hammer (ram) before impact is equal to the work done by the total pile resistance for the observed pile head permanent displacement (pile set) after a blow plus the energy dissipated inside the pile and within the soil during the blow, as well as the energy lost at impact in the various driving components between the hammer and the pile head. This can be written mathematically as:

$$e_h W_H H = Q_{ult}(s + s_c) \tag{1}$$

where W_H is the hammer (ram) weight; H is the hammer drop height; e_h is the hammer efficiency; Q_{ult} is the ultimate pile capacity; s is the observed pile set; and s_c is an empirical constant expressing the aforementioned energy losses and the energy stored temporarily inside the pile due to elastic compression during the blow process.

Eq. (1) has been the basis for development of most empirical pile driving formulas. The equation is solved for Q_{ult} with the input variable being the pile set s. The simplicity of these formulas, combined with budget limitations, has led to their significant use in practice. Pile driving formulas available in the literature include the Gates formula [4], the modified ENR formula [5], the Eytelwein formula [6], the Danish formula [7], the Janbu formula [7], the

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Pacific Coast Uniform Building Code (PCUBC) formula [3], the Canadian National Building Code formula [3], and the Navy-McKay formula [3]. Table 1 lists the five formulas that we use later for comparison purposes. Salgado [8] suggests that consideration of existing empirical formulas in deep foundation quality control is typically not advantageous since the safety factors recommended when they are used are large. McVay et al. [9] note that, although empirical dynamic formulas are very easy to use, their predictions are characterized by considerable scatter and, in some cases, bias. A critique of these formulas can be found in Likins et al. [10]. Attempts to improve pile driving formulas [11,12] have been only partly successful due to the complexities of the problem, a highly nonlinear wave propagation problem that involves complex mechanics. Recalibration of dynamic formulae to local conditions has been shown to substantially improve their predictive performance [13], but these formulae are constrained to regions where data is available. Improved pile driving formulas without these drawbacks and exhibiting less scatter would require lower factors of safety and would be useful in practice.

In this paper, we simulate the pile driving process using the soil reaction models described in detail in [14] and, based on the results from a series of parametric simulations, propose pile driving formulas that explicitly account for the soil and pile type and, as a consequence, exhibit reduced prediction scatter. Pile driving formulas are developed for five general cases: floating piles in clay, piles in uniform sand deposits, end-bearing piles in sand, end-bearing piles in clay and piles crossing soft clay and bearing on sand. Here the term end-bearing pile refers to a pile for which the base resistance is an appreciable fraction of the total pile resistance. The static pile capacities for these soil profiles were calculated using a set of recent static design methods [15].

Well-documented case histories of static load tests on driven piles are used to validate the proposed formulas. Moreover, the predictions of the proposed formulas are compared with those of existing formulas. In the next section, we present in detail the methodology followed to generate the proposed formulas, along with the necessary background information on static capacity calculation and dynamic pile driving analysis.

2. Static pile capacity calculations

The limit resistance (Q_L) of an axially loaded pile is the load at which a pile plunges through soil. An ultimate limit state is generally expected to be reached at loads less than the limit load. For piles in sand, the ultimate load $Q_{\rm ult}$ is defined as the pile load $Q_{10\%}$ that causes a settlement equal to 10% of the pile diameter B [16]. For piles in clay, except heavily overconsolidated clay, $Q_{\rm ult}$ is practically equal to Q_L, since the latter may be mobilized for a settlement less than 0.1B [8].

The ultimate pile resistance is the summation of the ultimate base resistance $Q_{b,\rm ult}$ and limit shaft resistance Q_{sL}:

$$Q_{\rm ult} = Q_{b,\rm ult} + Q_{sL} \tag{2}$$

The base resistance $Q_{b,\rm ult}$ is calculated using:

$$Q_{b,\rm ult} = q_{b,\rm ult} A_b \tag{3}$$

where $q_{b,\rm ult}$ is the ultimate unit base resistance and A_b is the area of the pile base.

The shaft resistance Q_{sL} is given by:

$$Q_{sL} = \sum_i q_{{\rm sL},i} A_{s,i} \tag{4}$$

where $q_{{\rm sL},i}$ is the limit unit shaft resistance along the segment of the shaft intersecting the ith sub-layer of the soil and $A_{s,i}$ is the corresponding shaft surface area.

The ultimate unit base resistance ($q_{b,\rm ult}$) and limit unit shaft resistance ($q_{\rm sL}$) of driven piles in sands and in clays are calculated in this paper using the Purdue design equations [15] summarized below.

For a pile base embedded in a sand layer, the limit unit base resistance ($q_{\rm bL}$) is set equal to the cone penetration resistance ($q_{\rm c}$), which may be estimated using the cone resistance relationship of Salgado and Prezzi [17]:

$$\frac{q_{\rm c}}{p_{\rm A}} = 1.64 \exp\left[0.1041\phi_c + (0.0264 - 0.0002\phi_c)D_{\rm R}\right]\left(\frac{\sigma'_h}{p_{\rm A}}\right)^{0.841-0.0047D_{\rm R}} \tag{5}$$

Table 1
Traditional pile driving formulas.

Formula	Equations[a]	Notes
Gates formula [4]	$Q_{\rm u} = a\sqrt{e_{\rm h}E_{\rm h}}(b - \log(s))$	s in mm a = 104.5 b = 2.4
Modified ENR [5]	$Q_{\rm u} = \left(\frac{1.25e_{\rm h}E_{\rm h}}{s+C}\right)\left(\frac{W_{\rm H}+n^2W_{\rm P}}{W_{\rm H}+W_{\rm P}}\right)$	C = 0.0025 m n = 0.5 for steel-on-steel anvil on steel or concrete piles
Danish formula [7]	$Q_{\rm u} = \frac{e_{\rm h}E_{\rm h}}{s+C_1}$ $C_1 = \sqrt{\frac{e_{\rm h}E_{\rm h}L}{2AE}}$	
Pacific Coast Uniform Building Code (PCUBC) formula [3][b]	$Q_{\rm u} = \frac{e_{\rm h}E_{\rm h}C_1}{s+C_2}$ $C_1 = \frac{W_{\rm H}+kW_{\rm P}}{W_{\rm H}+W_{\rm P}}$ $C_2 = \frac{Q_{\rm u}L}{AE}$	k = 0.25 for steel piles and 0.1 for all other piles
Janbu [3]	$Q_u = \frac{e_hE_h}{K_us}$ $C_d = 0.75 + 0.15\frac{W_P}{W_H}$ $K_u = C_d\left(1+\sqrt{1+\frac{\lambda}{C_d}}\right)$ $\lambda = \frac{e_hE_hL}{AEs^2}$	

[a] Symbols in formula equations: $Q_{\rm u}$ = predicted pile capacity (in kN), $e_{\rm h}$ = hammer efficiency; $E_{\rm h}$ = maximum driving energy of the hammer (in kJ); s = observed pile set (in m if not specified); $W_{\rm H}$ = weight of the ram (in kN); $W_{\rm P}$ = weight of the pile (in kN); L = length of the pile (in m); A = cross-sectional area of the pile (in m^2); E = Young's modulus of the pile material (in kPa).
[b] The calculation of predicted static capacity using PCUBC formula requires iterations.