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Discussions and Closures

Closure to "CPT-Based Axial Capacity Design Method for Driven Piles in Clay"

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This paper presents a closure to "CPT-Based Axial Capacity Design Method for Driven Piles in Clay" by Barry M. Lehane, Zhongqiang Liu, Eduardo J. Bittar, Farrokh Nadim, Suzanne Lacasse, Nezam Bozorgzadeh, Richard Jardine, Jean-Christophe Ballard, Pasquale Carotenuto, Kenneth Gavin, Robert B. Gilbert, Jens Bergan-Haavik, Philippe Jeanjean, and Neil Morgan. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002847.

The writers welcome the opportunity to respond to this discussion and to provide further clarity on aspects of the paper. The following comments address the main issues raised:

1. The database used to calibrate the method was compiled and audited by a large team of experts from 12 different organizations, universities, and companies. This unified database was published in Lehane et al. (2017) and differs in many respects from the database published in Lehane et al. (2013). Almost 50% of the cases included in Lehane et al. (2013) were not deemed suitable for inclusion in the unified database, which employed stringent selection criteria, as described and justified in Lehane et al. (2017).
2. The discusser is correct in his observation that there cannot be a consistent relationship between the ultimate shaft friction (τ_f) directly and the in situ undrained shear strength (s_u) and such inconsistency is borne out by the relatively poor predictive performance of simple alpha (α) methods, e.g., $\tau_f = \alpha s_u$. The relationship deduced in the paper between τ_f and the cone resistance q_t reflects observations made in instrumented pile load tests (which measured radial stresses acting on the pile shafts) indicating that installation radial total stresses vary directly with q_t; see Figs. 1, 2, 3(a), and 4(a) in the original paper. The normalized installation radial total stress (S_i) is only one component of Eq. (4) and the three other components, namely, (S_c/S_i), f_L, and tan δ, do not vary with q_t. The basis of the new method is therefore that the radial total stress acting on a pile shaft during installation (σ_{ri}) is proportional to the q_t value (and also varies with h/D); such proportionality can be appreciated from base resistance predictions that employ cavity expansion theory where σ_{ri} at the pile tip varies directly with q_t.
3. The relationship between τ_f and q_t indicated by the instrumented pile tests in Fig. 5 is only used to inform the database calibration and optimization analyses, leading to the derivation of Eq. (17). It is reassuring that Eq. (17) is consistent with the

J. Geotech. Geoenviron. Eng., 2023, 149(10): 07023013

lateral stress observations from these instrumented pile tests (most of which are not part of the unified database).

4. Figs. 1–4 of the discussion and the associated text deal with the effects of remolding and other factors influencing s_u. This discussion, while interesting, is not relevant to the paper, which does not examine relationships between τ_f and s_u.
5. The discusser mentions that it is desirable that a method errs on the conservative side with a mean ratio of measured to calculated capacity (Q_m/Q_c) less than unity. However, it is clear that any calibration of a design formulation against a database should seek to achieve $Q_m/Q_c = 1$ and allow designers to apply appropriate factors at a later stage to introduce the level of desired conservatism (consistent with a method's distribution of Q_m/Q_c values across a database).
6. The discusser quotes the mean value of Q_m/Q_c when assessing method performance. However, formulations for empirical methods usually involve a multiplier that is adjusted to give a mean Q_m/Q_c ratio of unity [e.g., the value of 0.07 in Eq. (17)]. Therefore, the variance of Q_m/Q_c ratios, and not the mean Q_m/Q_c ratio, provides the best reflection of the reliability of a formulation and the optimization analyses described in the paper were conducted to minimize the coefficient of variation of Q_m/Q_c.
7. The writers are fully supportive of the need to include the interface friction angle (δ) in formulations for shaft friction, but knowledge of δ alone is insufficient without a means of determining σ'_{rf}, which is far more challenging. Considerable developments have been made in the understanding and measurement of interface friction since Moore (1947).
8. In response to a number of potential specific limitations of the new method raised by the discusser:
   - The results from instrumented piles with diameters less than 220 mm were used to gain insights into key stress changes arising in the life of a displacement pile (Figs. 1–3 of the original paper) and are not part of the unified database used for the method calibration.
   - These instrumented pile tests were conducted in a wide range of soil types with varying compositions, OCRs, and sensitivities. As such, they provide very useful information regarding effects of various soil characteristics on shaft friction development.
   - The instrumented piles in Lierstranda clay illustrate the consequences of high sensitivity on the installation radial total stresses and the subsequent relaxation during equalization. Clays at the Borsa and Sandpoint test sites develop similarly low shaft frictions and also fall within Zone 1 of the soil behavior type chart. The original paper therefore recommends application of the reduction factor, F_{st}, for Zone 1 materials. The final line in the conclusion warns designers of inaccuracies in shaft friction estimates in these clays.
   - If a normalized stress term is defined as $S = (\sigma_r - u_0)/q_t$, then the ratio of the post-equalization term and the installation term is $S_c/S_i = \sigma'_{rc}/(\sigma_{ri} - u_0)$. This format allows the various components contributing to shaft friction to be represented in the simple way given in Eq. (4). The value of the ambient pore pressure (u_0) is subtracted from σ_r to be consistent with q_t values that are zeroed at the mudline in offshore cone penetration test (CPT) investigations (and zeroed at ground level for onshore investigations).
   - Figs. 3 and 5 of the original paper form bounds to sets of measurements of radial stresses obtained in instrumented pile tests. These provide background and support for the subsequent investigation of formulations to predict axial pile capacities of the unified database, which did not require extrapolation of Figs. 3 and 5 to h/D values up to 142.
9. The discusser is correct in stating that the best way to estimate axial capacity is to perform full-scale pile load tests. However, in the absence of such load tests, the method proposed in the original paper provides a rational means to obtain such estimates. The method has been shown to have a significantly higher reliability than existing methods [when tested against the unified and test pile load test databases described in the paper, as well as in a mixed soils database (Bittar et al. 2022)]. Future field and numerical research can explore means of estimating the four components of the equation for τ_f given in Eq. (4).
10. An important characteristic of the method presented in the original paper is that it does not relate shaft friction with undrained shear strength. The variability in N_{kt} values, cited by the discusser, is one contributor of the poorer reliability of s_u-based correlations with shaft friction. The direct nature of Eq. (7) eliminates uncertainties related to transformation to other possible correlating parameters such as s_u. For offshore piles, where piles are mostly driven and the main site investigation tool is the piezocone test, a CPT-based pile design method is clearly preferable.
11. The writers are in full agreement with the need for further instrumented pile load test data as well as well the reporting of well-documented full-scale pile tests. The use of reusable model test piles is certainly one tool that should be considered given the absence of any discernible scale dependence of Eq. (17) (as illustrated, for example, by the reasonable predictions obtained for small-diameter piles in the test database).

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