Design method reliability assessment from an extended database of axial load tests on piles driven in sand

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Abstract

Accurate axial capacity remains a challenging task for piles driven in sands. Rigorous database studies have become key tools for assessing the efficacy of design methods. This paper employs the 117 high quality entries in the recently developed ZJU-ICL database to check for potential biases between nine prediction procedures, considering a range of factors. The analysis highlights the critical importance of addressing age after driving, open and closed ends, tension versus compression and concrete compared to steel. It also shows the hierarchy of reliability parameters associated with the alternative approaches. The ‘full’ ICP approach and UWA approaches are found to have significant advantages in eliminating potential biases. It is also argued that design Load and Resistance or Safety Factors should be varied to match the design and site investigation methods applied, as well as the loading uncertainty and degree of load cycling, which often varies between applications. Noting that predictions for base capacities Q_b are inherently less reliable than for shaft Q_S, especially in rapidly varying ground profiles, credible lower bound parameters q_c are recommended for Q_b assessment. It is also recommended that the potential effects of cycling should be addressed carefully in cases that involve substantial environmental loading.

Keywords: Database assessment; driven piles; sand; capacity of pile; time effect

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Introduction of database development

The growing use of CPT testing, in combination with recent research and design method development, is improving the accuracy of axial capacity predictions for piles driven in sands; Jardine and Chow (2007), Schneider et al (2008). Rigorous checking against statistically significant numbers of field tests has been critical to assessing which 'CPT' methods offer advantages over conventional procedures. However, even large national test archives, such as the United States FHWA Deep Foundation Load Test Database (DFLTD) of 1307 tests involving a wide range of pile and soil types (Abu-Hejleh et al 2015) contain relatively few entries that offer the information required to test the 'CPT' calculation procedures reliably for piles driven in sand. Similar difficulties apply, for example, to the Laboratoire Central des Ponts et Chaussées (LCPC, now known as IFSTTAR) database of 174 tests on which the French national design methods rely; Bustamante and Gianeselli (1982), Burlon et al (2014).

Specialist databases have therefore been built to test the new 'CPT-based' design approaches, as summarised in Table 1. The database employed in this paper has grown from the 23 closed-ended tests on piles driven in sand assembled by Lehane (1992) and employed by Lehane and Jardine (1994) to assess their early version of the Imperial College Pile (ICP) design method, along with then the current American Petroleum Institute (API), LCPC and Toolan et al (1990) offshore design procedures. Chow (1997) identified and analysed 42 new sand cases, which she added to the above 23 records to help assess the reliability of the Jardine and Chow (1996) method for open and closed ended piles in comparison with the API and LCPC approaches.

Jardine et al (2005) added 18 further cases, including high quality tests on large steel open-piles, to build the database against which they tested the updated Imperial College Pile (ICP-05) procedures.

Parallel work at the University of Western Australia (UWA) augmented Chow's (1997) dataset with 26 previously unrecognized entries. Lehane et al (2005a, b) and Schneider et al (2008) applied quality filters that excluded, for example, tests without full CPT profiles. They employed their 77 remaining tests to assess the reliability of the UWA-05 capacity prediction method, along with ICP-05, the Main Text API and the Fugro-05 (Kolk et al 2005a) and Norwegian Geotechnical Institute (NGI-05, Clausen et al 2005) methods that had been derived from databases of 45 and 85 tests respectively. As summarised later, the Fugro-05 shaft calculation procedure simplified and re-calibrated the MTD expressions, while the UWA-05 shaft method extended from the same expressions to address open ended piles by a new 'effective area' approach. The methods employ a range of base resistance procedures.

A team from Zhejiang University (ZJU) and Imperial College London (ICL) has recently assembled an openly accessible 'CPT' database for piles driven in sand (http://mypage.zju.edu.cn/en/zxyang/682156.html) whose general characteristics are listed in Table 2. Of the 117 tests currently included, 54 originated in the ICP-05 set, a further 14 in the UWA-05 collection and 12 in the DFLTD database; the 37 other newly adopted cases derive from literature searches and the Authors' industrial and academic networks. Yang et al (2015a,b) describe the quality filters applied in assembling the ZJU-ICL database and give details of each test entry. Noting that the database and statistical analyses can be updated as new tests or design methods become available, the same Authors give preliminary indications of how predictions from a limited range of design methods compare with the capacities of the database piles.

The ZJU-ICL database's 117 tests represent a 70% increase in the total population that meet our stated quality criteria. This paper employs this resource to (i) offer a far more comprehensive assessment of the performance of eight total capacity design methods and one additional base capacity method and (ii) address significant shortfalls in previous studies and design guidance. For example, API RP2GEO now notes the advantages of 'CPT based' methods and sets out 'simplified' ICP-05 and UWA-05 versions. However, we show below that the 'simplified' methods may give significantly poorer predictions than the original 'full' methods. We also examine below potential factors that may influence the capacity of piles and result in potential biases with respect to:

- Loading sense (tension or compression)
- Pile material (concrete or steel)
- Pile dimensions and slenderness (L, D, L/D)
- Wall thickness ratios (D/t) for open ended piles

The selection of soil parameters, the potential impact of cyclic loading and the choice of safety or load and resistance factors are also discussed. The new database analysis follows a brief introductory recapitulation of the nine design methods and discussion on critical new evidence regarding the effects of ageing between driving and testing. However, our main focus is on the database analysis; references are cited that provide full details of the pile load tests, the calculation procedures and associated pile ageing studies.

Pile capacity calculation procedures

The shaft resistance of piles driven in sand can often be mobilized fully at axial head displacements smaller than 0.1D. Far larger displacements may be required to achieve full end bearing, especially with large open-ended piles. Such displacements cannot be tolerated in most practical applications, so compressive capacities are often defined as the maximum sum Q_{total} of the shaft Q_s and base Q_b capacities developed at displacements of up to 0.1D

$$Q_{total}=Q_s + Q_b= \pi D\int \tau_f dz + q_{b,0.1}A_b \qquad \text{Eq. (1)}$$

where τ_f is the local ultimate shaft friction; z is pile depth; $q_{b,0.1}$ is the end bearing available after a head displacement of 0.1D and A_b is conventionally defined as the full base area. End bearing is considered negligible under tension loading.

API Main Text method

The API 'Main-Text' method (API RP2GEO 2014) assumes that local shaft and base resistances grow initially in proportion to the free field vertical effective stress by factors that increase with grain size and relative density. The method does not recognize any relative pile tip depth dependency of shaft resistance, but specifies upper unit shaft and base resistance limits that also grow with grain size and relative density. API RP2GEO (2014) recognizes that the earlier guidance (eg API 2000) is non-conservative and inappropriate for loose sands. API RP2GEO notes that alternative 'CPT based' methods offer advantages and sets out versions of four such methods in its Commentary.

The ZJU-ICL database considered in this paper includes loose sand cases. Rather than exclude these in our method assessment, or only apply the API method to a subset of piles, we apply the API 2000 guidance to the loose sand sites. For simplicity we refer to predictions made by this hybrid of the 2014 and 2000 recommendations as corresponding to the 'API Main Text' method.

ICP-05 method

The MTD (Jardine and Chow 1996) and ICP-05 (Jardine et al 2005) sand procedures were developed from field research with highly instrumented ICP piles (Lehane et al. 1993 and Chow 1997) that showed how the radial effective stress acting on the displacement piles' shaft at any depth, z, below ground surface were controlled by the local sand state, as indicated by the local CPT q_c, the relative height of the point above the tip h (normalised by effective radius R^*) and free field vertical effective stress σ'_{v0}. The local radial effective stress was written in the ICP-05 as:

$$\sigma'_{rc} = f(q_c, h/R^*, \sigma'_{v0}) \qquad \text{Eq. (2)}$$

where the equivalent radius $R^* = R = D/2$ for closed-ended piles. Parallel tests on strain gauged open-ended piles indicated that the same function could be applied provided the equivalent radius was expressed as $R^* = (R^2_{outer} - R^2_{inner})^{0.5}$.

The procedure also incorporates the ICP field test finding that the Coulomb failure criterion applies at the pile-soil interface and that the local ultimate shaft friction τ_f is given by:

$$\tau_f = \sigma'_{rf} \tan \delta_f \qquad \text{Eq. (3)}$$

where δ_f is the constant volume interface shearing angle obtained from large displacement ring shear tests conducted; see Jardine et al. (2005). Ring shear tests involve a considerable degree of particle breakage, which makes the outcomes both more representative and less sensitive to grain size than small displacement direct shear tests; Ho et al (2011). The δ_f data are independent of initial relative density and their overall trends with initial mean grain size d_{50} run counter to those originally specified by API (2000). Site specific ring shear laboratory tests were recommended in the MTD and ICP-05 guidance documents, but both included indicative plots relating δ_f to sand grain d_{50} for steel piles. The latter were updated by Ho et al (2011) and Barmpopolous et al (2009) for steel and concrete shafts respectively, leading to the trends given in Fig. 1, which we apply in the analysis reported herein.

The local radial stress at failure σ'_{rf} is expected to differ from that resulting from installation σ'_{rc} and the ICP-05 method specifies expressions that allow for both the difference between compression and tension loading and the effect of restrained interface dilation $\Delta\sigma'_{rd}$ which adds to the shaft friction by an amount that increases with sand shear stiffness (calculated from q_c and σ'_{v0}) and pile roughness, but diminishes with increasing pile radius R. Pile end bearing is related directly to local CPT q_c through simple empirical expressions with q_c derived by Chow (1997) from field tests; these include an important dependency of unit base resistance q_b on absolute pile diameter. In variable sand profiles the calculations can depend critically on the design q_c evaluation method; see Yang et al (2015c).

In setting out the ICP-05 approach Jardine et al (2005) point out the markedly positive effects on shaft capacity of time and potentially negative impacts of cyclic loading, emphasising that ICP-05 aims to predict the medium-term static capacities available around one month after driving. They also discuss the design rules required to deal with unfavourable carbonate or mica sand cases and set out a rational reliability based approach for selecting design safety or load and resistance factors.

Simplified ICP-05 method

The simplified ICP method proposed in the API RP2GEO Commentary neglects the (diameter dependent) dilatancy $\Delta\sigma'_{rd}$ component and rounds other parameter values conservatively, while leaving the base capacity expressions unmodified. No quantitative analysis is offered by API RP2GEO regarding the potential impact on capacity predictions of adopting these simplifications.

UWA-05 method

The UWA-05 approach offers an elaboration of the ICP that retains Eq. (3) and the MTD guidance for determining δ_f while adding a new 'effective area' term to Eq. (2) for open ended piles that depends on the incremental core filling ratio developed during driving, which has to be predicted in design from an empirical relationship in which coring is expected to become progressively more effective during driving with larger piles. It also removes the mild dependency on σ'_{v0} and relates shaft friction to h/D rather than h/R^*. The base capacity expressions employ an effective area approach in place of the ICP's expressions. The assumed filling ratio-to-diameter relationship leads to the static base resistance q_b of open-ended piles reducing with inner diameter D_{inner}.

We have applied the updated 'ICP' guidance for δ_f given in Fig. 1 in the re-evaluation of the UWA-05 given in this paper.

Offshore UWA-05 method

The 'offshore version' of UWA-05 (Lehane et al. (2005a) listed in API RP2GEO's (2014) Commentary neglects the shaft dilatancy term and assumes a fully coring installation mode when calculating the effective area term implicit in the shaft radial effective stress and base capacity expressions.

Fugro-05 method

Kolk et al (2005b) also started from the 'MTD' expressions in setting out the Fugro-05 method. Their formulation, also listed in the API RP2GEO (2014) Commentary, neglects shaft dilatancy, employs h/R to model relative pile tip depth h or 'friction fatigue' (with a lower bound of 4) and employs fitting parameters calibrated against the Fugro-05 test database (see Table 1) but taking δ_f to be fixed at 29^o for all cases. Kolk et al considered the MTD end bearing expressions over-conservative and adopted an alternative q_b expression that is independent of pile diameter. The method was intended for steel offshore piles and makes no allowance for pile material.

NGI-05 method

The NGI-05 approach was derived from database trends through an empirical 'experience based' procedure. It offers a direct expression for the τ_f available at any given depth z that relies on assessing local relative density, rather than any direct use of q_c (Clausen et al 2005). Unlike the other three methods, it allows for the effect of relative pile tip depth h through a 'sliding triangle' (Toolan et al 1990) approach in which the reduction of local shaft resistance depends only on the relative depth z/L, where L is the final embedded shaft length. The latter 'friction fatigue' formulation does not depend on pile slenderness (h/D or L/D) and is independent of any absolute dimension (h, L or D). The NGI method incorporates factors to account for pile material, end conditions and loading sense (tension or compression).

LCPC-82 method

The 'experience based' Laboratoire Central des Ponts et Chausées (LCPC) CPT approach (Bustamante and Gianeselli 1982) assumes shaft τ_f/q_c ratios reduce with grain size and relative density from $q_c/60$ to $q_c/120$ with concrete and $q_c/120$ to $q_c/200$ with steel driven piles. Upper τ_f limits are specified that increase from 35 to 120 kPa and reduce with grain size and relative density. Base resistance q_b is assessed as 0.4 q_c (dense sand) to 0.5 q_c (looser sands and silt) and it is recognised that the base rules may not apply to large or long open ended piles. The procedures incorporate no 'h/R' (or friction fatigue) factor or any diameter dependence for base capacity.

HKU base method for open piles

Yu and Yang (2011) proposed a Hong Kong University (HKU) base capacity calculation method for open piles in which the influence zone depends on the embedded conditions, sand compressibility and q_c profile variations; q_b is more influenced by the soil beneath than above the pile tip, accounting for any weak substratum. Yu and Yang employ Plug Length Ratio (PLR, the plug-to-total length ratio at the end of driving) in their q_b procedure. In common with UWA-05, the PLR ratio and q_b are assumed to reduce with D_{inner}.

The various assumptions made concerning the effects of scale, geometry, ‘friction fatigue’ and pile material inevitably lead to spreads in the above eight calculation procedures’ predictions.

Statistical summary of database assessments

An important factor to consider next is the strong effect on shaft capacity of the time elapsed between pile driving and testing. While this trend is high-lighted by Jardine et al (2005) and its implications in reliability based design was explored by Yang and Liang (2009), pile age is not addressed explicitly in any of the other seven design procedures.

Effects of pile age and database filtering

Marked growth of capacity with time has been noted by multiple Authors, from Tavenas and Audy (1972) to Gavin et al (2015) and Rimoy et al (2015). Most field reports concern multiple re-tests on single piles. Base capacity is not thought to vary greatly with time and shaft capacity growth is best isolated by considering sets of identical “fresh” piles tested in tension after different ageing periods; Jardine et al. (2006), Gavin et al. (2013) and Karlsrud et al. (2014). Pre-failed and re-tested piles follow completely different, staggered and discontinuous, ageing trends. In particular, the rates of capacity growth are generally slower. Also the tendency of ‘fresh’ piles to show practically stable shaft capacities approximately one year after driving cannot be seen clearly in programmes of re-tests. Rimoy et al. (2015) brought together data from staged tension tests on sets of fresh, identical open steel pipe-piles (with $325\text{mm}<D<508\text{mm}$) driven to L/D ratios of 21 to 69 at the well characterised Dunkirk, Larvik and Blessington sites. They report that Q_m/Q_c, the ratio of measured (Q_m) capacities to those calculated (Q_c) by ICP-05, is less than unity at the End of Driving (EoD) but grows following an Intact Ageing Characteristic (IAC) before stabilising at ≈ 2.4 within a year[5]. Such large changes in capacity cannot be neglected in any representative database analysis.

Figure 2 presents on semi-logarithmic axes the ZJU-ICL total capacity dataset of tests conducted 3 to 300 days after driving, excluding here the 35 tests for which exact test ages were unknown. Checks with the ZJU-ICL base capacity dataset confirm Rimoy et al's conclusion that ageing affects shaft capacity primarily, so the tension tests are more affected by time than the total compression Q_{total} capacity; mixing tension and compression tests contributes to the scatter. Linear regression suggests that the ICP-05 predictions match the ZJU-ICL field data at around 10-15 days, with total capacity growing by approximately 50% per log cycle of time over the 100 to 200 days range. We consider in Fig. 3 only the shaft capacities listed in the ZJU-ICL database, retaining the same axes and showing the mean IAC trend from the tension tests collated by Rimoy et al (2015). The ZJU-ICL data are broadly compatible with Rimoy et al's IAC, although they suggest slightly slower and less marked shaft capacity growth. In Fig. 3a the ZJU-ICL tests are grouped according to their L/D ratios, while in Fig. 3b the grouping is by absolute pile diameter D. Overall, ageing appears insensitive to slenderness (L/D). Rimoy et al (2015) argue that ageing may be less significant with small diameter piles; new tests are underway to test this conjecture in the field.

Short term static testing can be undertaken to assess early age pile capacities, but dynamic

[5] While Q_m/Q_c is the natural ratio to employ in characterising capacity growth over time, the inverse is widely recognised as the more rational measure to employ in reliability analyses of predictive procedures.

analysis of the final driving blows is more common. Rimoy et al (2015) treat EoD and 1-day static capacities as being equivalent and recommend averaging of the often scattered dynamic EoD capacities as well as applying a compression-to-tension shaft capacity correction of 0.75 to estimate short term tension capacities for comparison with tension tests on aged piles. Applying similar procedures to the ZJU-ICL pile tests for which such information is available and allowing for base capacities in any cases where shaft and base EoD components were not disaggregated, leads an average 1 day or EoD-to-ICP shaft capacity ratio of ≈ 0.8.

Systematic growth, by a factor of ≈3, of shaft capacity over the first year after driving introduces significant bias between tests of different ages and questions which age should be implicit in any design method. Difficult choices have to be made in approaching this issue. Pile age bias could be reduced by normalising to a function, such as the IAC in Fig. 2, although this could be interpreted as biasing the outcomes. Alternatively, appropriate age tolerance limits could be employed, but at the expense of a diminished database population and reduced statistical precision. If, for example, a 13 ±10 day age range was adopted, the effects of time could be kept within ±20%. However, this step would reduce the number of pile tests by 75%.

The analysis that follows applied a 10 to 100 day age range to balance the desire of maintaining a statistically significant number of tests with a wish to limit potential age effects. While other choices could be made, this filter left 80 tests centred (logarithmically) on a nominal one month age. However, the older piles in the database are likely to have higher shaft capacities than their younger counterparts.

Ideally, only instrumented tests would be included in the database, so that shaft and base capacities could be distinguished reliably in compression tests. However, only 20 such tests could be identified. Adding 24 tension tests led to a total of 44 cases in which it shaft capacity could be identified.

Table 3 summarises the tests (from 13 countries) while Fig. 4 presents histograms that illustrate the distributions of: pile age, total capacity, diameter/width, length and average relative density for each shaft and toe. Points to note include:

1. All cases that fall outside the 10-100 day age range are excluded. However, the 35 entries whose ages are unknown are assumed to fall within the target range, which was considered typical of practical pile test ages.
2. Most piles developed capacities below 6 MN; only 6 tests exceeded 10 MN.
3. The diameters and lengths are concentrated in the 200 to 800 mm and 5 to 45 m ranges.
4. The average relative densities classify as medium to very dense over most shafts. The toe regions show wider variations because their averages are computed over shorter depth intervals.
5. In total 32 tests (at 7 sites) involved sands whose average relative densities fall outside the range over which the current API Main Text applies.

Evaluation of eight total capacity methods

Total capacity

The eight methods' predictions for the 80 'age-filtered' ZJU-ICL cases are summarised in Table 4 and Fig. 5 in terms of the Q_c/Q_m means μ and CoVs (established assuming arithmetic rather than log-normal distributions and shown as ± values). Table 4 also adds for reference assessments made against the tests entered into the original ICP and UWA databases. An additional row is provided in Table 4 that reports the results obtained from the full, unfiltered, ZJU-ICL database. The influence of the few late tests (conducted after >100 days) exceeds that of the more numerous early age (<10 day) tests, leading to generally lower Q_c/Q_m ratios. Overall, we note:

- Broad agreement with the equivalent comparisons reported by Jardine et al. (2005) and Schneider et al. (2008).
- Overall mean Q_c/Q_m values spanning from 0.68 to 1.25 over all the cases covered and CoVs from 0.30 to 0.55, with the Main Text API giving consistently higher CoVs than the CPT approaches.
- The 'full' ICP and UWA methods giving significantly lower CoVs (0.30 to 0.35 respectively) than the other CPT-based approaches (0.47 to 0.48) as well as mean overall Q_c/Q_m μ values that are closer to unity (0.94 to 1.05, compared with 1.20 to 1.23).
- The LCPC-82 CPT procedures giving broadly similar outcomes to the Fugro-05 and NGI-05 methods.
- The 'simplified ICP' and 'offshore' UWA having significantly lower μ values and larger CoVs than their 'full' versions. Their degrees of fit do not improve as pile diameter increases and the ICP simplifications lead to unnecessary conservatism.
- The 'full' UWA version appears marginally non-conservative, suggesting that the 'offshore' version may be preferable for design, despite its higher CoV.

- A tendency for all methods to under-predict the shaft capacities, as measured in the 20 instrumented compression and 24 tension 10 to 100 day age tests. This is interpreted as being due primarily to the shaft ageing trends discussed above. All eight shaft methods appear to predict capacities at earlier mean ages after driving.

Open-ended shaft and base capacity

One of the key differences between the design methods is how they allow for open-ended conditions. The time-filtered ZJU-ICL dataset was used to check for Q_c/Q_m scatter and bias related to end condition, giving the results presented in Table 4. In only total 21 (tension and compression) shaft cases could be considered and compared with the overall trends. Adding two additional tests (TP4 and TP5 from Kikuchi et al 2007, whose main shaft sections penetrated through clays) increases the limited base capacity dataset to 13 cases. Considering the shaft first, no method led to a mean Q_c/Q_m significantly greater than unity for open pile shafts and the CoVs were also lower than for total capacity in most cases. Moving to open-ended base resistance, the methods that apply CPT q_c data directly give lower CoVs than those that do not (i.e. NGI-05 and API). It also appears that all approaches except the ICP and HKU methods have non-conservative bias, especially those that do not incorporate diameter dependency: Fugro-05, NGI-05, API and LCPC-82. However, the dataset is small and the statistical outcomes could be sensitive to minor changes in the number of entries.

Loading sense

While the API and LCPC methods assume that similar shaft capacities are developed under compression and tension loading, the other 'CPT methods' adopt discounted parameters or factors when calculating tension capacity. Jardine et al (2005) argued that lower shaft capacities develop in tension because: (i) the Poisson's straining under axial load leads to the pile contracting radially and unloading the soil mass, rather than bulging outward and imposing additional radial and vertical stresses and (ii) the major principal stress axis direction imposed by tension loading is rotated away from that applying at the EoD. The age filtered ZJU-ICL database was employed to examine the possible statistical biases applying to loading sense effect, considering 20 compression piles in which shaft capacity could be identified and 24 tension piles. In addition to revealing a generally conservative bias, which is probably due to pile age as explained earlier, Table 4 appears to indicate a tendency for all eight design methods to over compensate for the difference between tension and compression loading. The ICP (simplified and full) shows the smallest offsets related to loading sense (0.06 and 0.1 respectively), while the UWA and ICP approaches both lead to marginally conservative means and lower CoVs in tension than compression. The LCPC method appears significantly non-conservative in tension, with the largest μ offset, while the API leads to the highest CoV in tension. The other methods give intermediate trends.

A further point to note is that the higher CoVs seen for compressive shaft capacities. As noted earlier, the latter can only be determined from the relatively few instrumented pile tests included in the database. In addition, difficulties in interpreting strain gauge measurements and allowing for base stresses locked in by driving reduce the reliability of compression shaft capacity determination and add to its scatter.

Pile material

A second key difference, which is particularly important in mainstream civil engineering applications, is the way the methods consider pile material. Only NGI-05 and LCPC-82 stipulate different parameters for steel and concrete piles. The ICP-05 procedure recommends determining δ_f from ring-shear tests conducted with the appropriate interface material. We apply here the revised guidance given in Fig. 1 that indicate lower δ_f values applying against concrete shafts, even when they have similar roughnesses ($R_{CLA} \approx 10\mu m$) to industrial steel piles.

Grouping the various methods' predictions according to material type leads to the outcomes given in Table 4 for shaft (tension and compression) capacity. In general, the API and LCPC methods show the largest and most non-conservative offsets between the mean Q_c/Q_m values applying to concrete and steel piles. All except Fugro-05 indicate lower CoVs for steel piles and the full ICP-05 and UWA-05 approaches appear the least sensitive to pile material type. The allowance made for concrete piles in LCPC-82 appears to be non-conservative. However, the relatively low number (N = 10) of concrete pile tests limits the confidence with which conclusions can be drawn without further high quality field tests.

Pile dimensions

Slenderness ratio

Jardine and Chow (1996) and Schneider et al. (2008) showed that incorporating the 'h/R^*' and h/D factors identified from highly instrumented pile tests into their shaft capacity expressions allowed the ICP-05 and UWA-05 CPT based methods to eliminate the Main Text API method's strong skewing with respect to both sand relative density and pile slenderness L/D. The ZJU-ICL database shows similar trends, as demonstrated for L/D by the Q_c/Q_m scatter plots given by each total capacity method in Fig. 6 and for shaft capacity alone (separating compression and tension cases) in Fig. 7. The regression line established through the scattered API data points indicates the most marked skewing with respect to L/D, confirming that the method's lack of any h/R or friction fatigue factor leads to over-conservative bias at low L/D, while the full ICP-05 and UWA-05 methods indicate the least. The plots also underscore the Simplified ICP-05 and Offshore UWA-05 shaft methods' tendency to be systematically over-conservative.

Diameter dependence

Designing piles whose diameters fall outside the test dataset (Fig. 2 and Table 3) involves assuming that the calculation method can extrapolate the field tests reliably. However, as summarised earlier, the available methods incorporate a wide range of assumptions regarding the dimensional dependence of base and shaft components.

We consider base resistance first, noting that (i) there are no reliable tests on closed-end large diameter piles and (ii) the HKU method is only applicable to open-ended piles. Open (N=20) and closed (N=13) base capacities are distinguished in Fig. 8, which reports how the alternative methods' overall Q_c/Q_m trends vary with diameter D. Although limited to 33 tests, it is clear that the diameter-dependency built into ICP-05, UWA-05 and HKU leads to less scatter and skew than the diameter-independent Fugro, NGI, API or LCPC expressions, which become less conservative with increasing *D*, although ICP-05 may be slightly conservative with large piles. Linear regression fitting indicates that an ascending order of bias applies to the Fugro, NGI, API and LCPC methods.

We move next to consider the potential biases of shaft capacity with *D*. As noted by Knudsen et al. (2012), the ICP, UWA and Fugro methods all employ 'friction fatigue' relationships that are normalised to depend on h/R^* or h/D, while NGI-05 is independent of pile dimensions (or L/D) and the API and LCPC-82 neglect 'friction fatigue' altogether. Although countered by the full ICP's and UWA's shaft dilation components being inversely dependent on diameter, shaft capacity calculations tend to show, for piles of fixed length, average shaft resistance q_s growing with diameter for ICP-05, UWA-05 and Fugro-05. Only data from the 44 instrumented compression and tension tests can be included in the scatter diagrams presented in Fig. 9, which suffer from the uncertainties mentioned earlier related to ageing, strain-gauge interpretation and locked-in base loads. While LCPC-82 appears to suffer from a significant degree of (conservative) bias with respect to D, the dataset appears to be too scattered to draw further conclusions.

Length dependence

In addition to the effects of pile slenderness (L/D) discussed above, API and LCPC-82 include absolute upper limits to τ_f, while the ICP, UWA and Fugro approaches incorporate lower limits to the h/R or h/R* ratios that should be substituted into their shaft capacity calculations. A further consideration is the fundamental cause of the decay of radial shaft stresses with relative pile tip depth, *h*. If this was related principally to geometrical effects it would scale with diameter *D* or R^*, while if it was dominated by shaft load cycling during driving it might scale with the number of pile blows, and so generally increase with the absolute values of *h* or *L*. All of these factors could lead to different trends for Q_c/Q_m with L. Recent instrumented model pile tests suggest that, above a limited number of cycles, geometrical effects dominate (Jardine et al 2013). However, as with pile diameter, it is important to check for any bias when considering which of the methods is safer to apply when designing piles with lengths that fall outside the ZJU-ICL database.

Figure 10 presents the eight methods' scatter diagrams for shaft Q_c/Q_m against absolute pile length. As in Fig. 9, the ICP-05 and NGI-05 approaches appear to lead to the least bias, despite their different 'friction-fatigue' formulations.

Wall thickness ratio effect

Open-ended pipe piles are driven with a range of pile diameter to wall thickness ratios, D/t. Ratios between 15 and 45 are typical in offshore oil and gas (Jardine and Chow 2007), but offshore wind turbines often adopt far higher ratios and civil engineering concrete pipe piles can have D/t <5; Yang et al (2015c). Allowance is made for open or closed ends in all the methods except the LCPC-82 approach, but only ICP-05 and UWA-05 incorporate an influence of D/t on shaft capacity, through the former's h/R^* normalisation and the latter's 'effective base area' terms.

The full set of 21 open-ended (tension or instrumented compression) ZJU-ICL pile tests from which shaft capacity can be determined are shown in Fig. 11, plotting Q_c/Q_m against D/t for all eight methods. While the degree of scatter is large for the Fugro-05 and LCPC-82 cases, their regression lines suggest upward (non-conservative at high D/t) bias. This trend is clearer for the API method, while the ICP, UWA and NGI trend lines are principally flat.

Parameter section and reliability in service

In setting out the ICP-05 procedures Jardine et al (2005) employed reliability-based arguments to comment on the safety or load and resistance factors required to meet target probabilities that foundations could carry the intended loads safely under stated conditions. To be meaningful, such calculations should address total uncertainty through the biases and CoVs applying to loads and capacities. Jardine et al (2005) suggested that the statistics found with routine offshore design methods for piles driven in sand were incompatible with the desired reliability levels when combined with currently recommended safety or load and resistance factors. While reliability can be improved by adopting lower CoV CPT based methods, more stringent factors than are currently employed in routine offshore practice appear necessary to achieve suitably low failure probabilities.

In principle, the design factors should be varied to match the reliability of the design and site investigation methods applied, as well as the loading uncertainty – which varies between applications. Designers should also account for pile age (Jardine et al 2005, Yang and Liang 2009, Rimoy et al 2015) spatial variability, the greater uncertainty associated with base resistance than shaft and the relatively large displacements required to mobilise tip loads. Noting that spatial variability in CPT parameters makes it is harder to establish statistically reliable predictions for base Q_b values than to predict the integrated effects of varying q_c profiles on shaft Q_S, Jardine et al (2015) recommend applying credible lower bound base q_c design parameters while continuing to adopt cautiously interpreted mean q_c trends for pile shaft resistance. Base capacity may provide an additional reserve under compressive loading, but only at the expense of large settlements developing.

Onshore design codes typically require more conservative safety, load and resistance factors than are employed offshore. In addition, pile load tests are often carried out to check performance and reduce the likelihood of problems in service. Jardine and Chow (2007) discuss the low incidence of reported offshore field failures, noting that the trend towards higher-than-average relative densities in marine sands and the strong shaft ageing trends identified in Fig. 2 had the potential to overcome other non-conservative aspects of conventional approaches. Recent research (see for example Rimoy et al 2015) has strengthened the case regarding pile ageing. Recent field re-strike tests have added confirmation that large offshore piles gain capacity markedly with time after driving in sand; see for example Jardine et al (2015). However, Jardine et al (2012) and Andersen et al (2013) also argue that designers should move to address more routinely the potentially negative effects of load cycling on axial capacity. While low level load cycling can be mildly beneficial (Jardine and Standing 2012, Tsuha et al 2012) high level cycling can cause marked and rapid shaft capacity losses.

Conclusions

The following main conclusions are drawn:

1. The accurate prediction of axial capacity remains challenging for piles driven in sands.
2. Rigorous database studies are key to assessing the potential efficacy of design methods. Analysis of the Zhejiang University/Imperial College London (ZJU-ICL) expanded test database has provided a more comprehensive assessment of the potential predictive biases and scatters of nine design procedures than was possible previously.
3. The analysis presented herein highlights the critical importance of addressing: (i) pile age after driving, (ii) open and closed conditions, (iii) open piles' D/t ratios, (iv) different tension and compression loading responses and (v) concrete versus steel pile construction.
4. The database analysis identify the hierarchies of reliability parameters associated with each approach. The 'full' ICP approach and UWA methods have significant advantages in helping to eliminate potential bias and scatter. Noting that compressive shaft capacity measurements are subject to more scatter than tension equivalents, the UWA and ICP methods show better fitting trends for both (i) shaft-to-base capacity splits and (ii) the relative magnitudes of tension and compression shaft resistances.
5. The 'simplified' ICP approach offers no practical advantage over the 'full' ICP and leads to unnecessarily conservative predictions at the pile scales covered by the database.
6. Base capacity measurements and predictions are inherently more difficult and less reliable than those for shaft resistance. It is recommended that credible lower bound q_c parameters should be applied for end bearing assessment in varying ground profiles.
7. Cyclic loading effects should also be addressed carefully.
8. Design Load and Resistance or Safety Factors should be varied to match the reliability of

the design and site investigation methods applied, as well as the loading uncertainty.

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References

Abu-Hejleh, N.M., Abu-Farsakh, M., Suleiman, M.T., Tsai, C. (2015). Use and development of deep foundation load test databases, *94th Transportation Research Board Annual Meeting*, in press.

American Petroleum Institute (API). (2000). Recommended practice for planning, designing, and constructing fixed offshore platforms-Working stress design, API RP2A, 21st Ed., Washington, DC.

American Petroleum Institute (API). (2014). ANSI/API recommended practice 2GEO, 1st Ed., RP2GEO, Washington, DC.

Andersen, K.A., Puech, A.A., Jardine, R.J. (2013). Cyclic resistant geotechnical design and parameter selection for offshore engineering and other applications, *Paris, TC-209 Workshop, 'Design for cyclic loading: piles and other foundations'*, Publisher: Presses des Ponts, 9-44

Barmpopoulos, I.H., Ho, T.Y.K., Jardine, R.J., and Anh-Minh, N. (2009). The large displacement shear characteristics of granular media against concrete and steel interfaces. *Proc. Research Symposium on the Characterization and Behaviour of Interfaces* (*CBI*). Atlanta, Frost, J.D. Editor, IOS Press, Amsterdam, 17-24.

Burlon, S., Frank, R., Baguelin, F., Habert, J., and Legrand, S. (2014). Model factor for the bearing capacity of piles from pressuremeter test results-Eurocode 7 approach. *Géotechnique*, 64(7), 513-525.

Bustamante, M., and Gianeselli, L. (1982). Pile bearing capacity by means of static penetrometer CPT. *2nd Eur. Symp. On Penetration Testing*, Amsterdam, 493-500.

Chow, F.C. (1997). Investigations into displacement pile behaviour for offshore foundations. PhD thesis, Imperial College, London, UK.

Chow, F.C., and Jardine, R.J. (1997). Applying the new Imperial College piles design methods to large open-ended piles in clay and sand. *Proc. 8th Int. Conf. on the Behaviour of Offshore Structures* (*BOSS*), Delft, Pergamon Press (UK), 109-124.

Clausen, C.J.F., Aas, P.M., and Karlsrud, K. (2005). Bearing capacity of driven piles in sand, the NGI approach. *Proc., Int. Symp. On Frontiers in Offshore Geotechnics*, Taylor & Francis, London, 677-681.

Gavin, K.G., Igoe, D.J.P., and Kirwan, L. (2013). The effect of ageing on the axial capacity of piles in sand. *Proceedings of the ICE-Geotechnical Engineering*, 166(2), 122-130.

Ho, T.Y.K., Jardine R.J., and Anh-Minh, N. (2011). Large-displacement interface shear between steel and granular media. *Géotechnique*, 61(3), 221-234.

Jardine, R.J., and Chow, F.C. (1996). New design methods for offshore piles. *Marine Technology Directorate (MTD) Publication 96/103*. London: MTD.

Jardine, R.J., and Chow, F.C. (2007). Some developments in the design of offshore piles. *Proc. 6th Int. Conf. on Offshore Site Investigations and Geotechnics*, Society for Underwater Technology, London.

Jardine, R.J., Puech, A., and Andersen, K.H. (2012). Cyclic loading of offshore piles: potential effects and practical design. *Proceedings of the 7th International Conference on Offshore Site Investigation and Geotechnics: Integrated Geotechnologies – Present and Future*, 59-97.

Jardine, R.J., Chow, F.C., Overy, R., and Standing, J.R. (2005). ICP design methods for driven piles in sands and clays, Thomas Telford, London.

Jardine, R.J., Standing, J.R. (2012). Field axial cyclic loading experiments on piles driven sand. *Soils and Foundations*, 52(4), 723–736.

Jardine, R.J., Standing, J.R., and Chow, F.C. (2006). Some observations of the effects of time on the capacity of piles driven in sand. *Géotechnique*, 56(4), 227-244.

Jardine, R.J., Thomsen, N.V., Mygindt, M., Liingaard, M.A., and Thilsted, C.L. (2015). Axial capacity design practice for North European wind-turbine projects. *Proc. Int. Symp. On Frontiers in Offshore Geotechnics III (ISFOG)*, Taylor & Francis Group, London, V. Meyer (Ed.), 581-586.

Karlsrud K., Jensen T. G., Wensaas Lied E. K., Nowacki F. and Simonsen A.S. (2014). Significant ageing effects for axially loaded piles in sand and clay verified by new field load tests. *Offshore Technology Conference*, Houston, doi:10.4043/25197-MS.

Kikuchi, Y., Mizutani, T., and Yamashita, H. (2007). Vertical bearing capacity of large diameter steel pipe piles. *Proc., Int. Workshop on Recent Advances of Deep Foundations*, Taylor & Francis, London, 711–716.

Knudsen, S., Langford, T., Lacasse, S., and Aas, P.M. (2012). Axial capacity of offshore piles driven in sand using four CPT-based methods. *In Offshore Site Investigation and Geotechnics: Integrated Technologies-Present and Future*. Society of Underwater Technology, 449-457.

Kolk, H.J., Baaijens, A.E., and Sender, M. (2005a). Design criteria for pipe piles in silica sands. *Proc., Int. Symp. on Frontiers in Offshore Geotechnics*, Taylor & Francis, London, 711-716.

Kolk, H.J., Baaijens, A.E., and Vergobi, P. (2005b). Results of axial load tests on pipe piles in very dense sands: The EURIPIDES JIP. *Proc. Int. Symp. on Frontiers in Offshore Geomechanics, ISFOG*, Taylor & Francis, London, 661-667.

Lehane, B.M. (1992). Experimental investigations of pile behaviour using instrumented field piles. PhD thesis, Imperial College, London, UK.

Lehane, B.M., Jardine, R.J., Bond, A.J. and Frank, R. (1993). Mechanisms of shaft friction in sand from instrumented pile tests. *J. Geotech. Engng. Div.*, ASCE, 119(1), 19-35.

Lehane, B.M., and Jardine, R.J. (1994). Shaft capacity of driven piles in sand: a new design approach. *Proc. Conf. on the Behaviour of Offshore Structures* (*BOSS*), 23-36.

Lehane, B.M., Schneider, J.A., and Xu, X. (2005a). A review of design methods for offshore driven piles in siliceous sand. *UWA Rep. No. GEO 05358*, The Univ. of Western Australia, Perth, Australia.

Lehane, B.M., Schneider, J.A., and Xu, X. (2005b). The UWA-05 method for prediction of axial capacity of driven piles in sand. *Proc. Int. Symp. On Frontiers in Offshore Geomechanics ISFOG*, Taylor & Francis, London, 683-689.

Mayne, P.W. (2013). Private communication, FHWA Deep Foundation Load Test Database (DFLTD).

Rimoy, S., Silva, M., Jardine, R.J., Yang, Z.X., Zhu, B. T., and Tsuha, C.H.C. (2015). Field and model investigations into the influence of age on axial capacity of displacement piles in silica sands.

Géotechnique, 65(7), 576-589.

Rücker, W., Karabeliov, K., Cuéllar, P., Baeßler, M., and Georgi, S. (2013). Großversuche an Rammpfählen zur Ermittlung der Tragfähigkeit unter zyklischer Belastung und Standzeit. *Geotechnik*, 36(2), 77-89.

Schneider, J.A., Xu, X., and Lehane, B.M. (2008). Database assessment of CPT-based design methods for axial capacity of driven piles in siliceous sands. *Journal of Geotechnical and Geoenvironmental Engineering*, 134(9), 1227-1244.

Tavenas, F. and Audy, R. (1972). Limitations of the driving formulas for predicting the bearing capacities of piles in sand. *Canadian Geotechnical Journal*, 9(1), 47–62.

Tsuha, C.H.C., Foray, P.Y., Jardine, R.J., Yang, Z.X., Silva, M., and Rimoy, S. (2012). Behaviour of displacement piles in sand under cyclic axial loading. *Soils and Foundations*, 52(3), 393-410.

Toolan, F.E., Lings, M.L. and Mirza, U.A. (1990). An appraisal of API RP2A recommendations for determining skin friction of piles in sand. Houston, Texas: *Proceedings of the 22nd Annual Offshore Technology Conference*, 33-42.

Yang, L., and Liang, R. (2009). Incorporating setup into load and resistance factor design of driven piles in sand. *Canadian Geotechnical Journal*, 46(3), 296-305.

Yang, Z.X., Jardine, R.J., Guo, W.B., Chow, F. (2015a). A new and openly accessible database of tests on piles driven in sands, *Géotechnique Letters*, 5 (January–March), 12-20.

Yang, Z.X., Jardine, R.J., Guo, W.B., Chow, F. (2015b). A comprehensive database of tests on axially loaded piles driven in sands, Zhejiang University Press – Elsevier.

Yang, Z.X., Guo, W.B, Zha, F.S, Jardine, R.J., Xu, C.J., Cai, Y.Q. (2015c). Field behaviour of driven Pre-stressed High-strength Concrete piles in sandy soils, *Journal of Geotechnical and*

Geoenvironmental Engineering, ASCE, 141(6), 04015020.

Yu, F., and Yang, J. (2011). Base capacity of open-ended steel pipe piles in sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(9), 1116-1128.

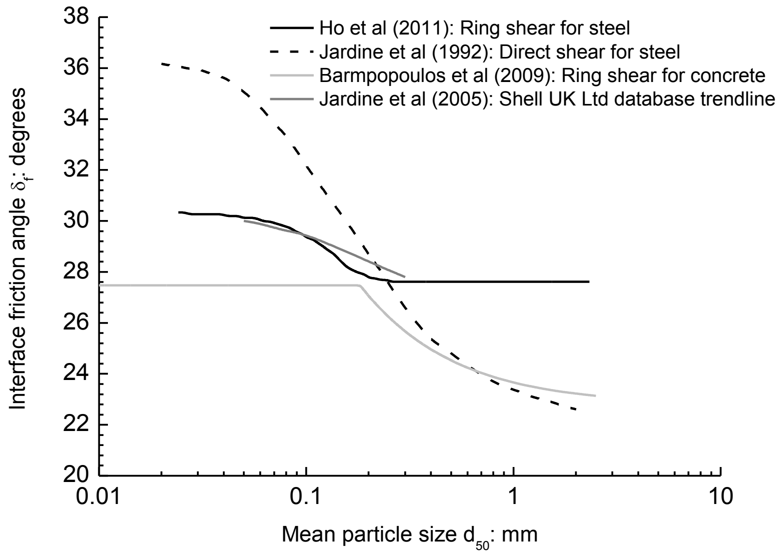


Fig. 1 Comparison of the trends of mean particle size and interface friction angle for silica sand

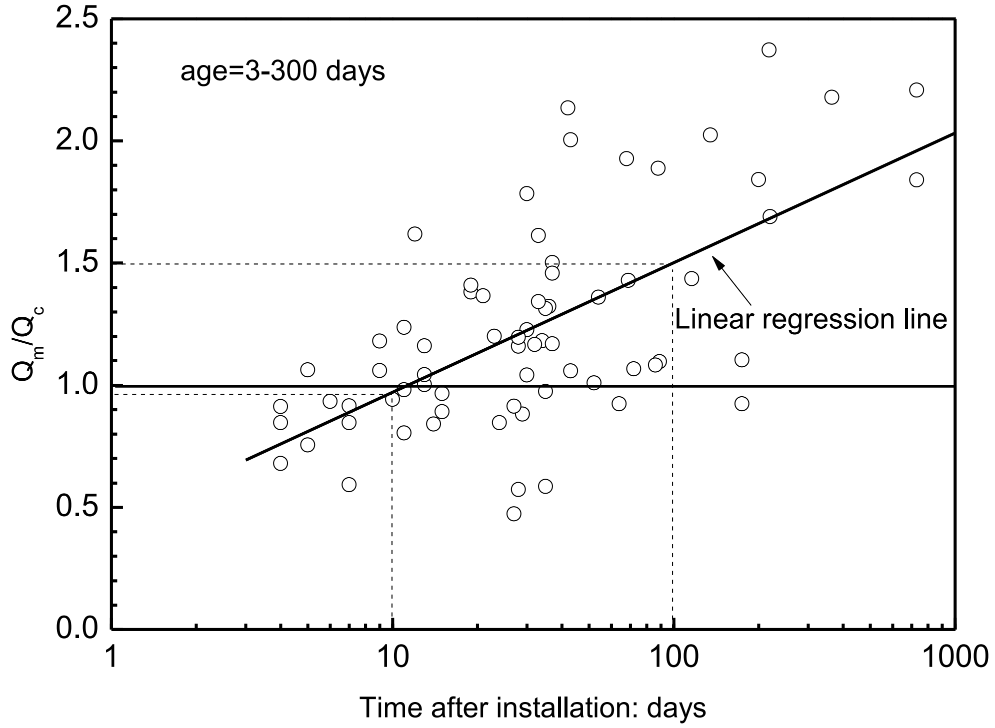


Fig. 2 Ratio of Q_m/Q_c measured total capacity to calculated capacity from ICP-05 against test pile age after driving

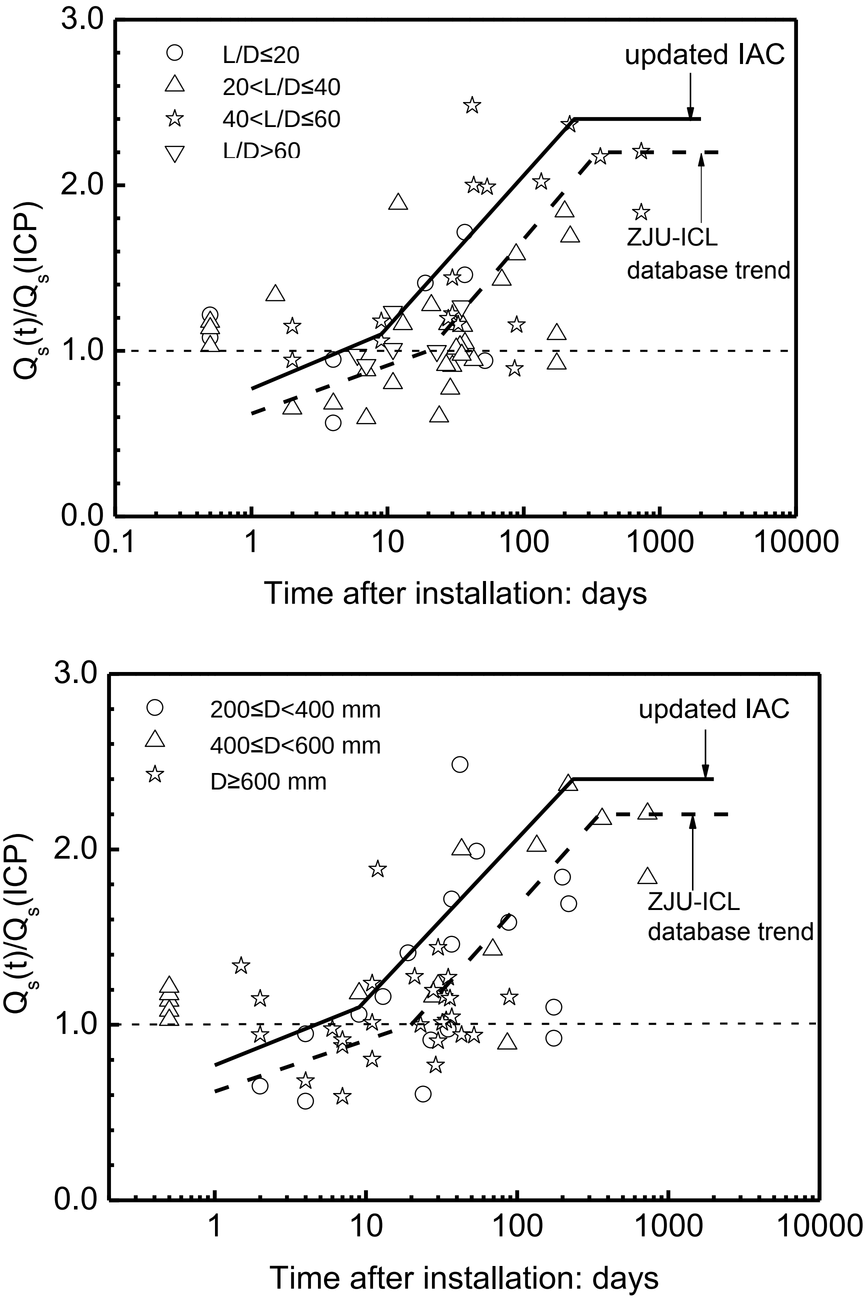


Fig. 3 Measured shaft capacity normalised by ICP-05 shaft capacity against time after installation distinguishing (a) four ranges of *L*/*D* ratios; (b) three ranges of outside pile diameters *D*

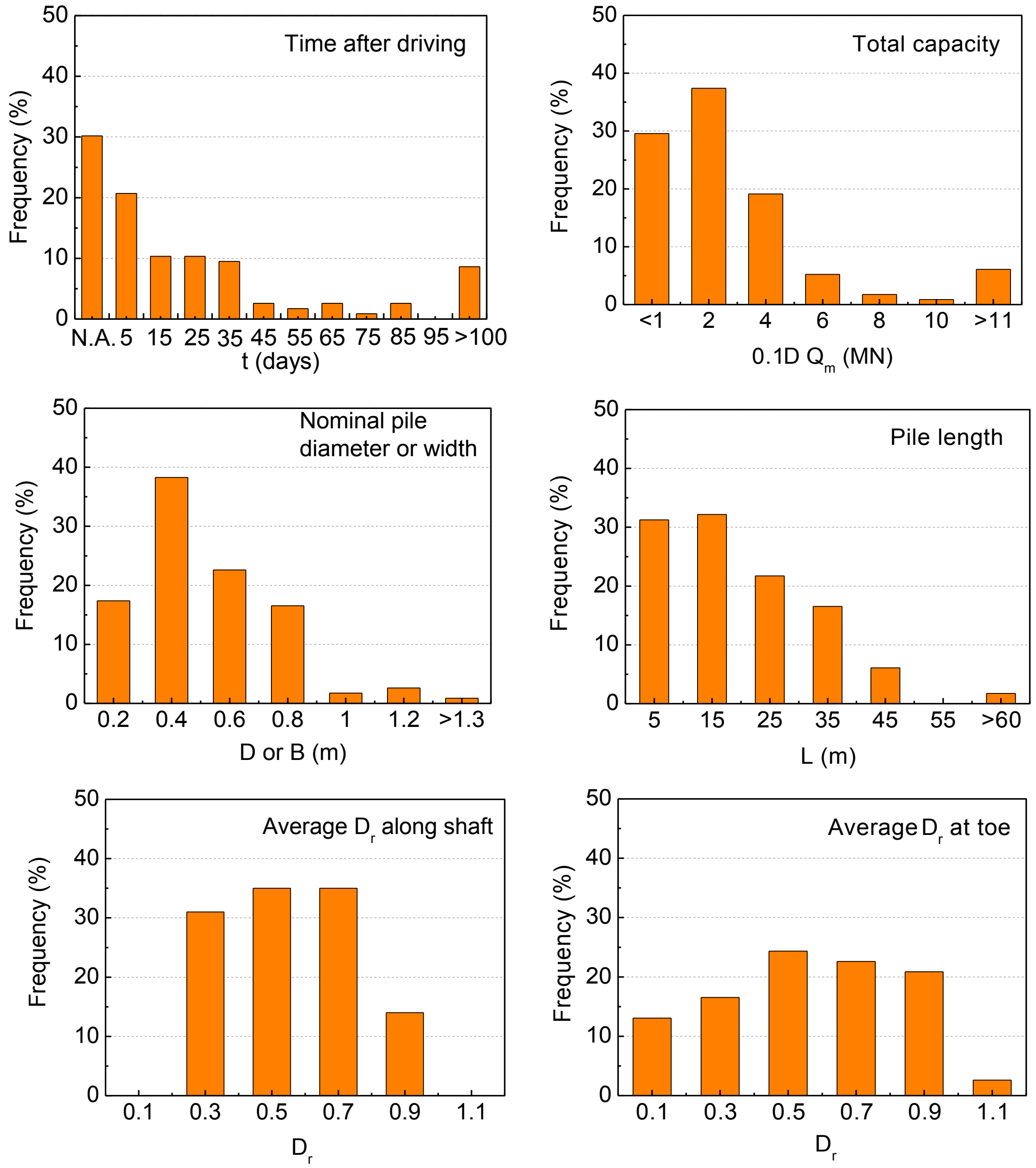


Fig. 4 Histograms for soil and pile parameters of ZJU-ICL database

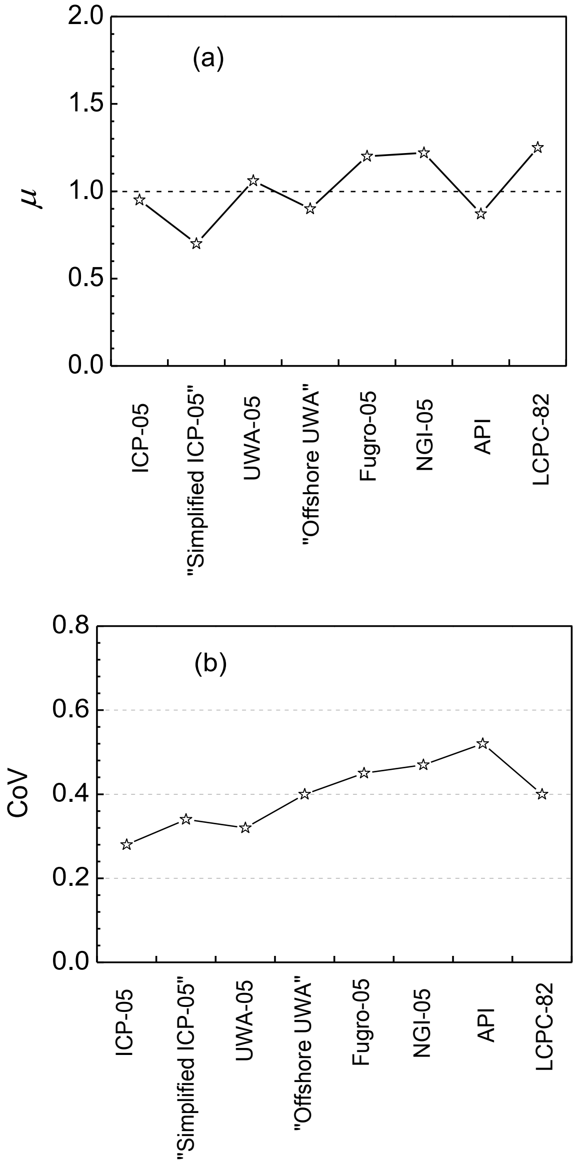


Fig. 5 Statistical values (μ and CoV) of total capacity for design methods based on filtered ZJU-ICL 10-100 day age database

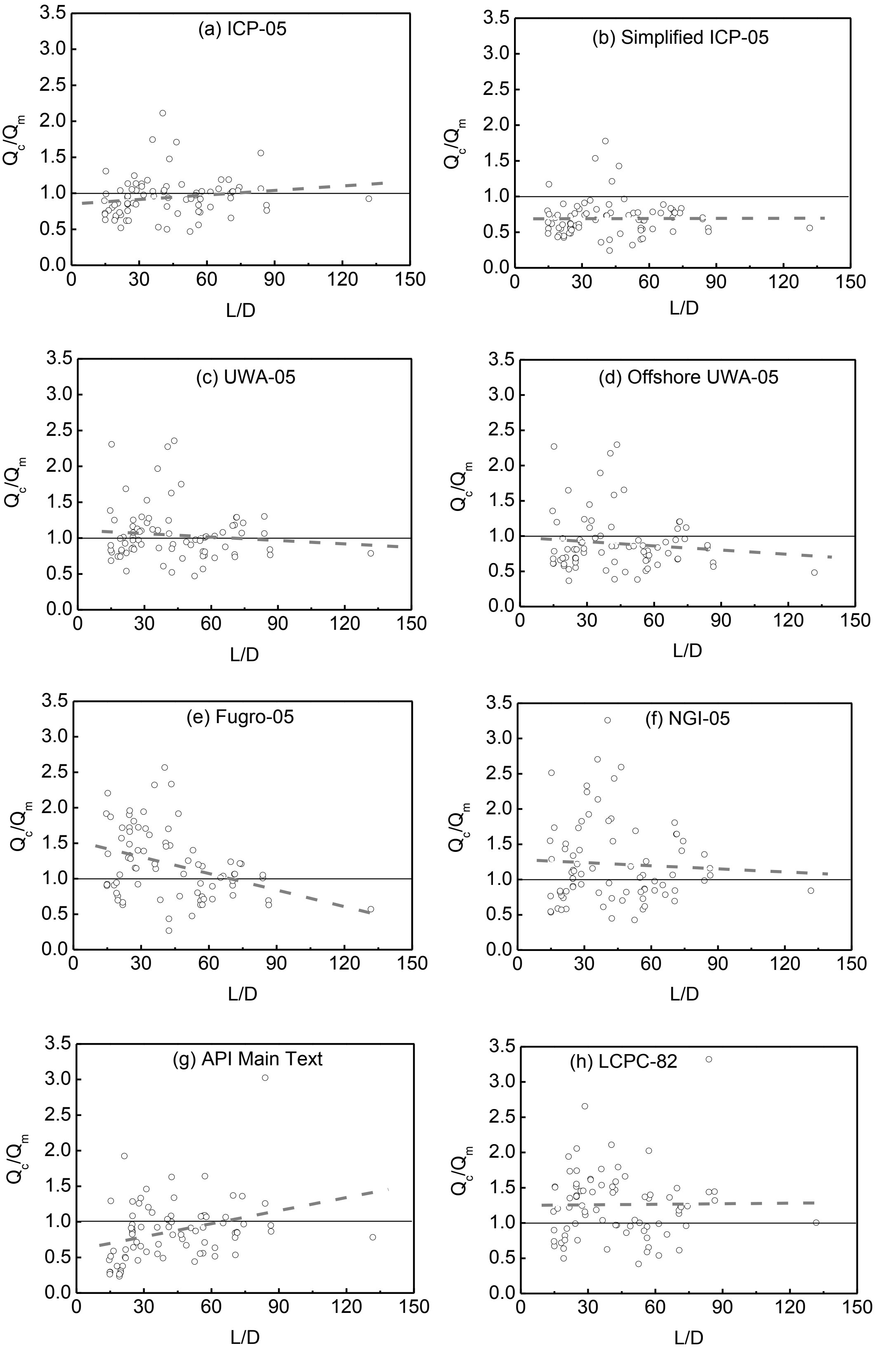


Fig. 6 Distribution of Q_c/Q_m (for total capacity) with respect to pile slenderness ratio L/D
(a) ICP-05; (b) "Simplified" ICP-05; (c) UWA-05; (d) "Offshore" UWA-05; (e) Fugro-05; (f) NGI-05; (g) API Main Text; (h) LCPC-82 – tested against filtered ZJU-ICL 10 to 100 day age dataset. Linear regression dashed lines are shown on the plots.

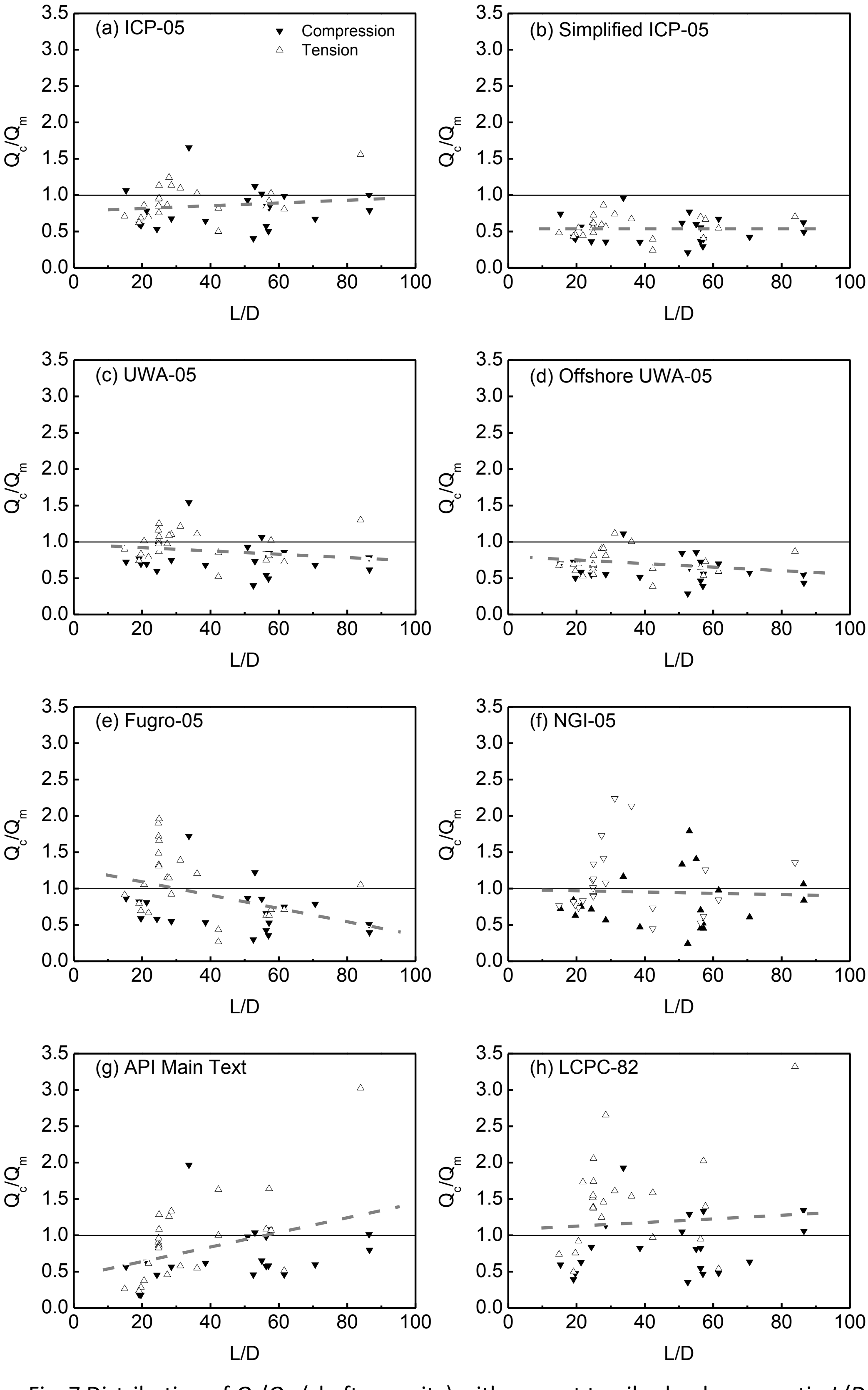
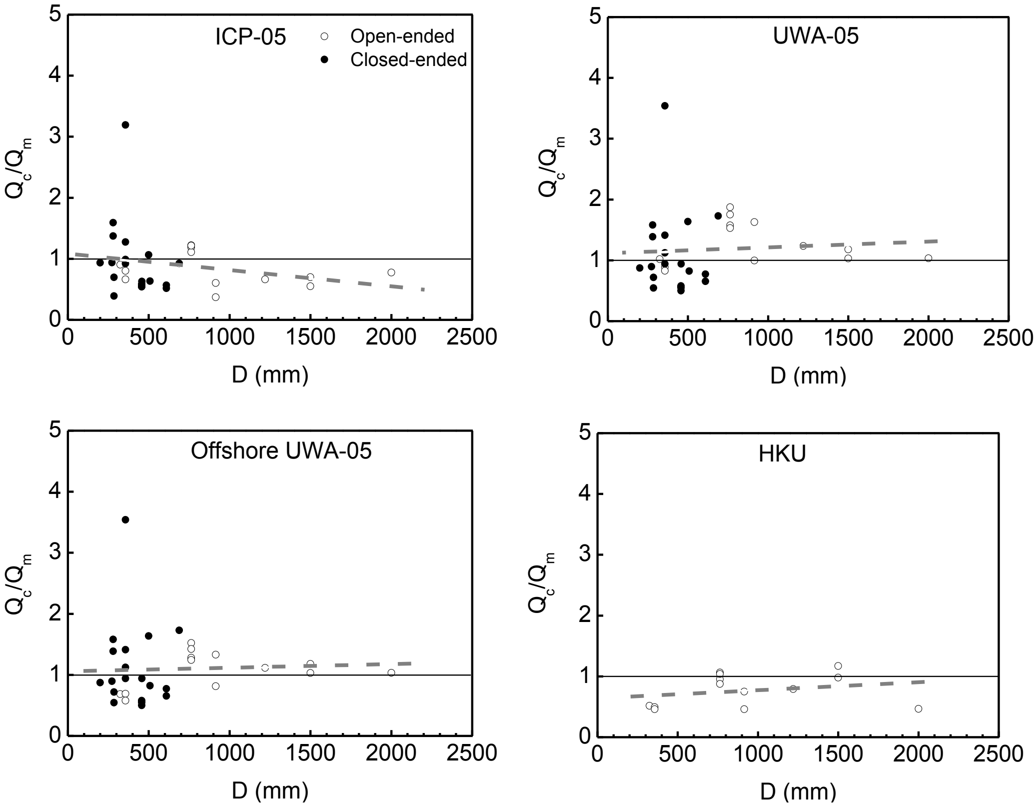
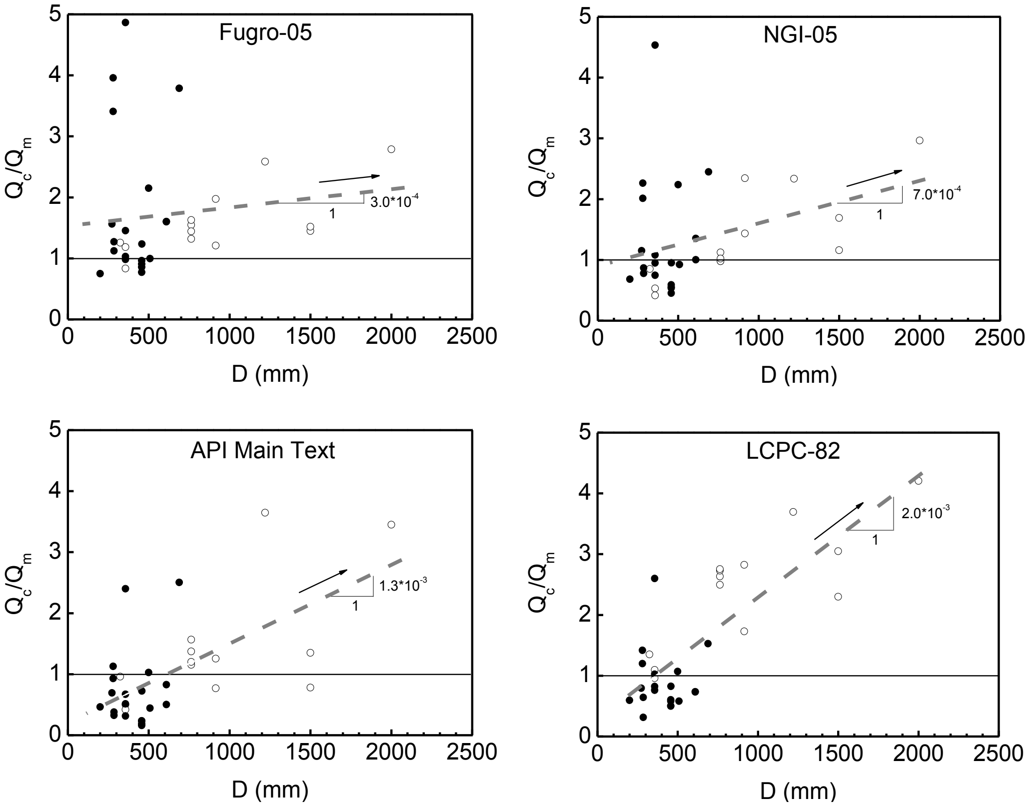


Fig. 7 Distribution of Q_c/Q_m (shaft capacity) with respect to pile slenderness ratio L/D (a) ICP-05; (b) "Simplified" ICP-05; (c) UWA-05; (d) "Offshore" UWA-05; (e) Fugro-05; (f) NGI-05; (g) API Main Text; (h) LCPC-82 – tested against filtered ZJU-ICL 10 to 100 day age dataset for both compression and tension piles. Linear regression dashed lines are shown on the plots.



(a) no dependency with pile diameter *D*



(b) strong dependency with pile diameter *D*

Fig. 8 Distribution of Q_c/Q_m (base capacity) with respect to pile diameter for both open and closed piles. Linear regression dashed lines are shown on the plots.

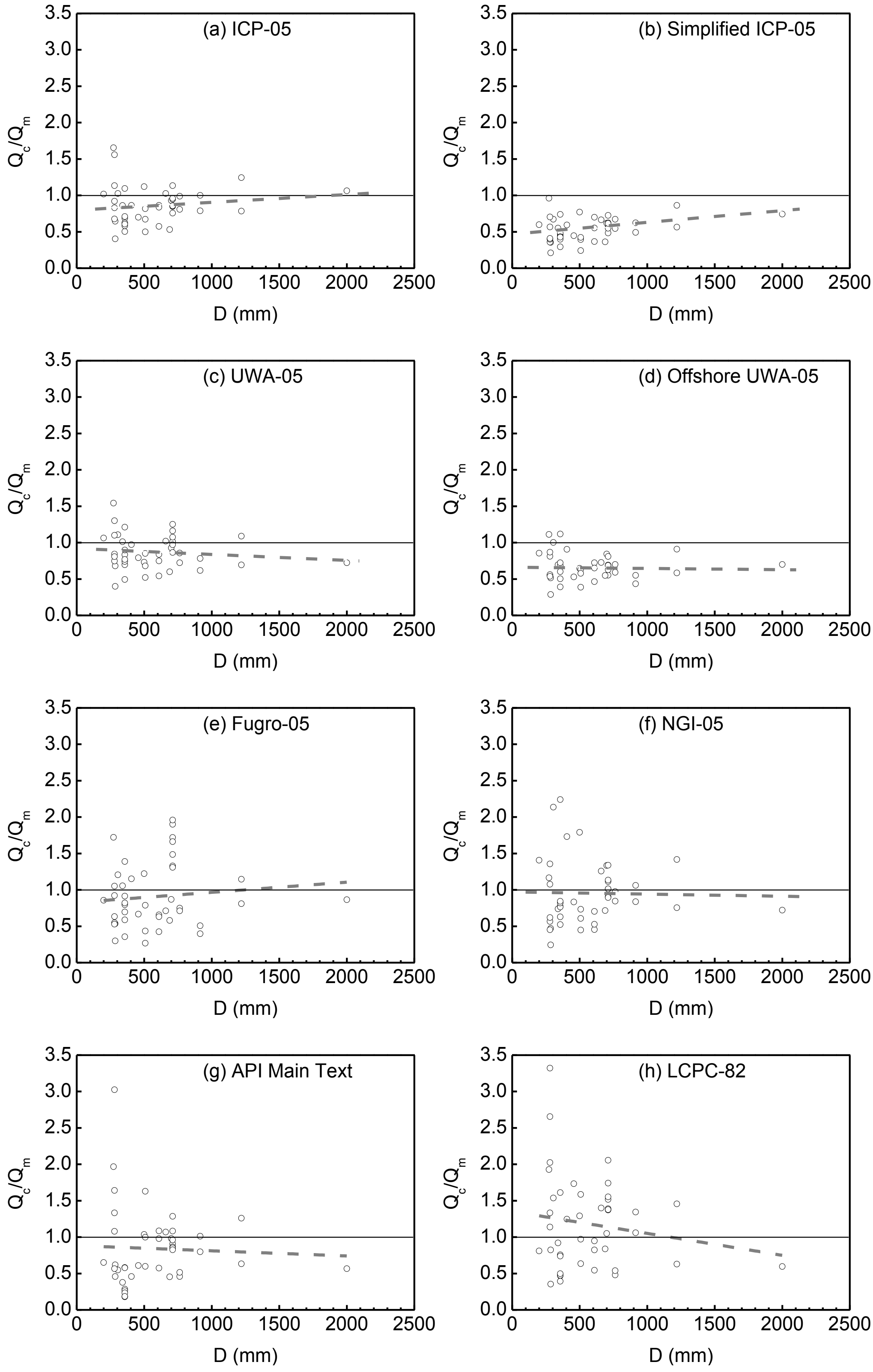


Fig. 9 Distribution of Q_c/Q_m (shaft capacity) by ICP-05 with respect to pile diameter D
(a) ICP-05; (b) "Simplified" ICP-05; (c) UWA-05; (d) "Offshore" UWA-05; (e) Fugro-05; (f) NGI-05; (g) API Main Text; (h) LCPC-82 – tested against filtered ZJU-ICL 10 to 100 day age dataset. Linear regression dashed lines are shown on the plots.

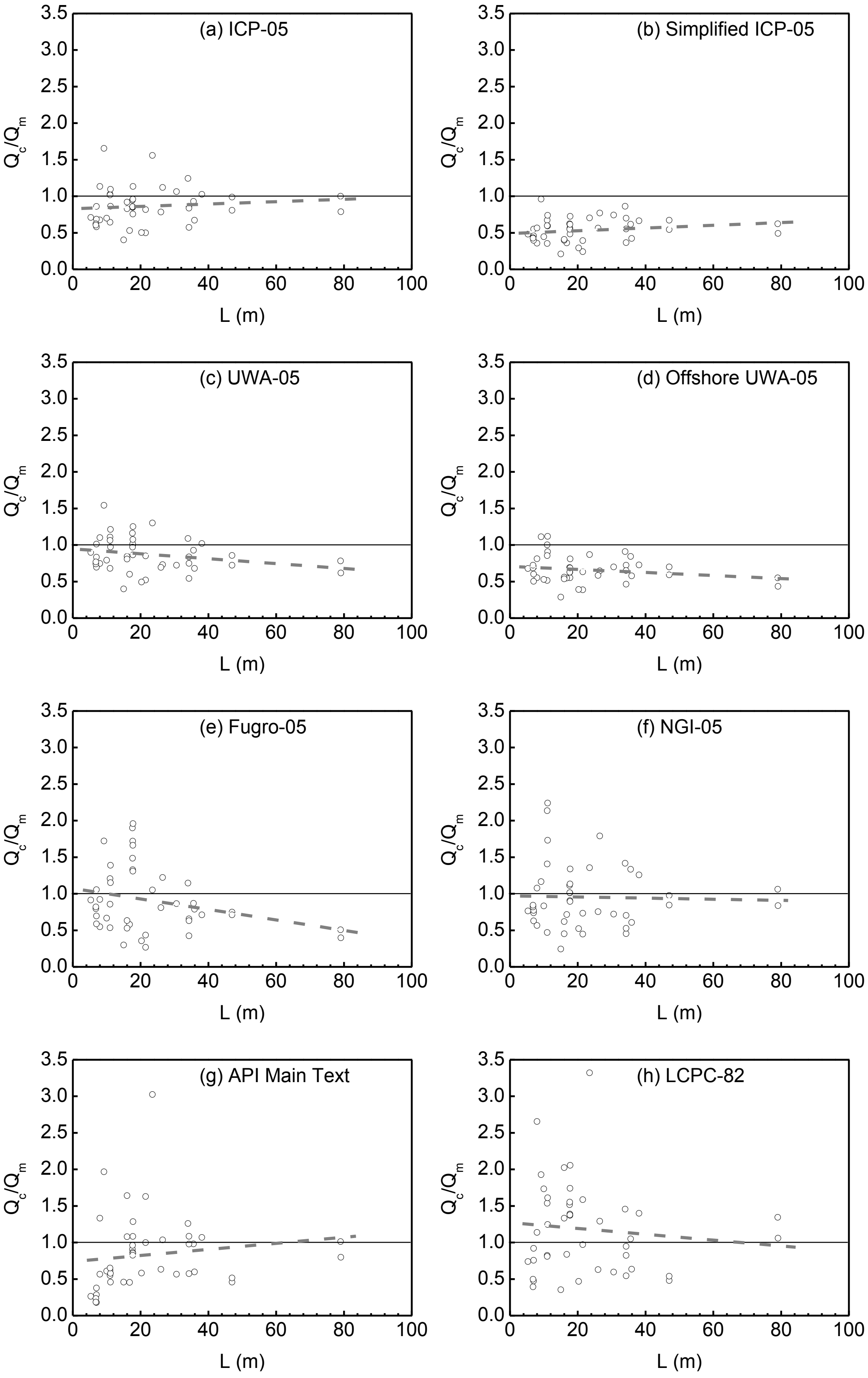


Fig. 10 Distribution of Q_c/Q_m (shaft capacity) by ICP-05 with respect to pile length *L*

(a) ICP-05; (b) "Simplified" ICP-05; (c) UWA-05; (d) "Offshore" UWA-05; (e) Fugro-05; (f) NGI-05; (g) API Main Text; (h) LCPC-82 – tested against filtered ZJU-ICL 10 to 100 day age dataset. Linear regression dashed lines are shown on the plots.

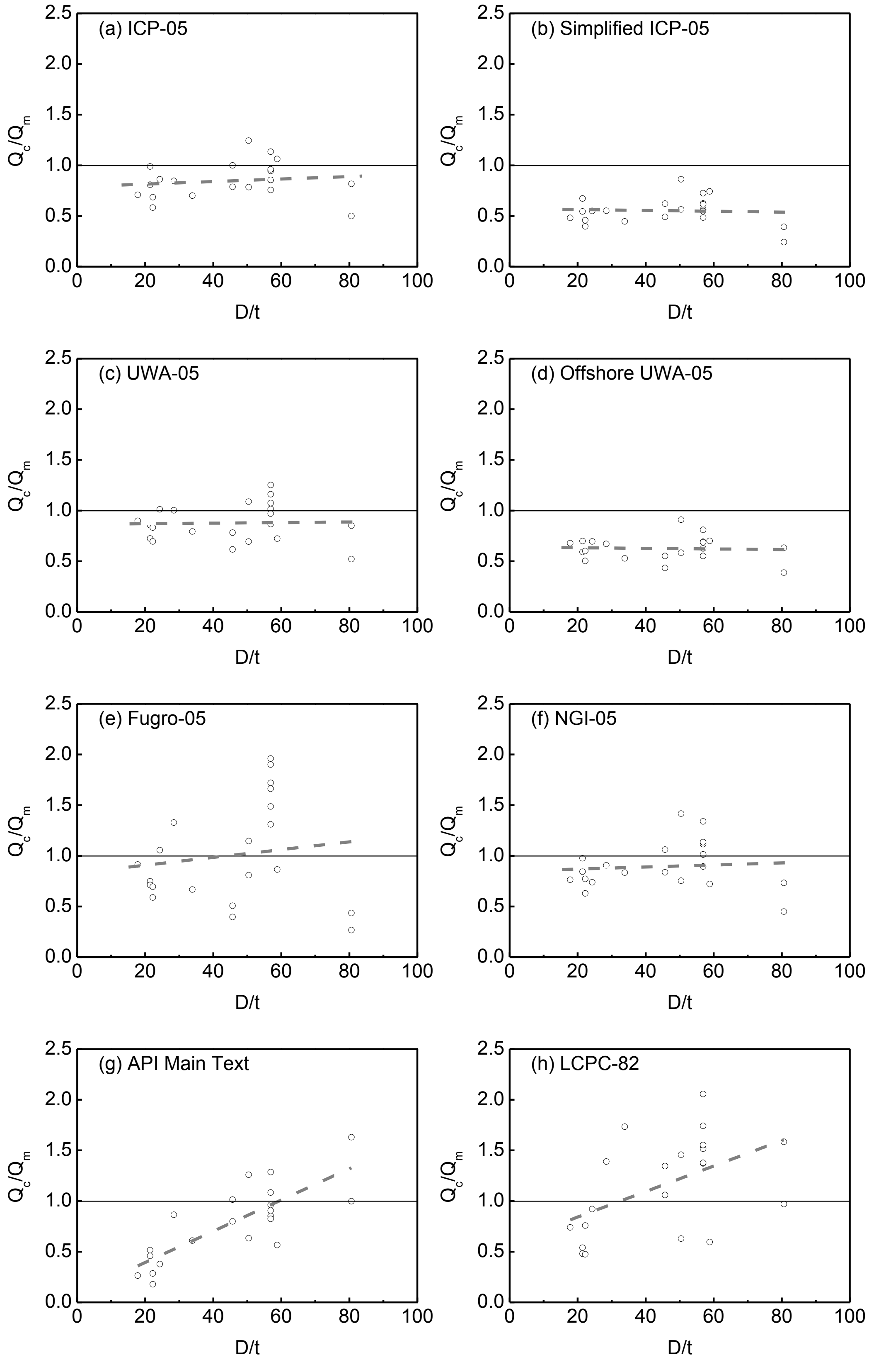


Fig. 11 Distribution of Q_c/Q_m (shaft capacity) with respect to pile diameter to wall thickness ratio D/t (a) ICP-05; (b) "Simplified" ICP-05; (c) UWA-05; (d) "Offshore" UWA-05; (e) Fugro-05; (f) NGI-05; (g) API Main Text; (h) LCPC-82 – tested against filtered ZJU-ICL 10 to 100 day age dataset. Linear regression dashed lines are shown on the plots.

Table 1 Summary of major databases for pile load tests in sand

Database reference adopted herein	Driven piles		Other piles	Total	Accepted by ZJU-ICL Sand Database	References
	Open-ended	Closed-ended				
ICP-94	0	23	0	23	11	Lehane and Jardine 1994
ICP-97	24	31	10	65	24	Chow and Jardine 1997
ICP-05	42	31	10	83	54	Jardine et al. 2005
UWA-05	32	42	0	74	65	Lehane et al. 2005a
	33	44	0	77	65	Schneider et al. 2008
NGI-05	23	57	5	85	19	Clausen et al. 2005
Fugro-05	27	18	0	45	25	Kolk et al. 2005a
LCPC	5	14	34	53	0	Burlon et al. 2014
DLFTD	10	238	318	566	12	Mayne 2013

Table 2 General characteristics and quality criteria of ICP, UWA and ZJU-ICL Databases.

	ICP-05	**UWA-05**	**ZJU-ICL (2015)**
Total no of tests in each database	83	77	117
Provenance of tests brought into each database	19 new, adding to 64 from ICP-97	26 new, adding to 51 from ICP-97	49 new, adding to 54 from ICP-05 and 14 from UWA-05
Pile types	Mainly driven piles, but with 8 jacked and 1 vibro-driven	Only driven piles	Only driven piles
Pile Shape	Circular, square, and octagonal piles	Circular, square and octagonal piles	Circular, square and octagonal piles
Pile diameter (mm)	200~2000	200~2000	200~2000
Pile length (m)	5.3~46.7	5.3~79.1	5.3~79.1
Soil description	Mainly siliceous sands, carbonate contents less than 15%, shaft length in clay less than 40%	Pile tips bearing a siliceous sand and siliceous sand contributes > 50% of shaft capacity	Pile tips bearing a siliceous sand and siliceous sand contributes > 65% of shaft capacity
Load test	Static; base and shaft capacity separated individually	Static	Static
Failure criterion	If no clear peak indicated in compression, pile head displacement of 0.1D (outer diameter); Failure in tension was usually well defined.	If no clear peak indicated in compression, pile head displacement of 0.1D (outer diameter); Tension was defined as the maximum uplift load minus pile weight	If no clear peak indicated in compression, pile head displacement of 0.1D (outer diameter); Tension was defined as the maximum uplift load minus pile weight
Age on testing	Pile tests were conducted 0.5 to 200 days after driving. Average age after driving =34 days after driving. Time details were reported in 74% of case records	Time between driving and load testing is typically 0.5 to 200 days (average t=24 days). Time details were reported in 77% of the case records	Pile tests were conducted 0.5 to 220 days, with an average of t=33 days after driving. Time details were reported in 65% of the case records

Table 3 Summary of ZJU-ICL database

	All entries			Filtered entries with age= 10-100 days		
	Closed	Open	All	Closed	Open	All
Number of piles	62	55	117	48	32	80
Steel	25	48	73	18	26	44
Concrete	37	7	44	30	6	36
Tension tests	10	31	41	8	16	24
Compression tests	52	24	76	40	16	56
Average length L (m)	17.6	25.2	21.2	18.9	26.0	21.8
Range of lengths L (m)	6.2-45	5.3-79.1	5.3-79.1	6.2-45	5.3-79.1	5.3-79.1
Average of diameter D (m)	0.413	0.645	0.522	0.422	0.667	0.520
Range of diameter D (m)	0.2-0.7	0.324-2.0	0.2-2.0	0.2-0.7	0.324-2.0	0.2-2.0
Average of density D_r (%)	54	60	57	54	61	57
Range of D_r (%)	28-89	30-88	28-89	31-89	30-87	30-89
Average test time after installation	35	80	61	43	28	35

Table 4 Summary of ZJU-ICL assessment of total capacity statistics (mean ± CoV of Q_c/Q_m ratios) for API, LCPC-82, and CPT methods

Database	ICP-05		UWA-05		Fugro-05	NGI-05	API	LCPC-82	HKU
	Full	Simplified	Full	Offshore					
Total capacity for all piles									
ICP (N=54)	0.97±0.35	0.69±0.38	1.00±0.32	0.84±0.38	1.11±0.41	1.16±0.50	0.87±0.66	1.23±0.49	Not applicable
UWA (N=65)	0.93±0.34	0.69±0.37	1.00±0.32	0.85±0.38	1.12±0.42	1.19±0.49	0.83±0.63	1.21±0.47	
Age Filtered ZJU-ICL data (N=80)	0.94±0.30	0.68±0.35	1.05±0.35	0.89±0.45	1.20±0.47	1.23±0.48	0.88±0.55	1.25±0.40	
Total ZJU-ICL data (N=117)	0.92±0.32	0.67±0.41	1.01±0.34	0.85±0.41	1.15±0.54	1.13±0.47	0.85±0.53	1.20±0.40	
Shaft capacity for open-ended piles									
Age Filtered ZJU-ICL data (N=21)	0.85±0.21	0.55±0.27	0.88±0.22	0.63±0.19	1.01±0.58	0.90±0.26	0.78±0.60	1.01±0.38	Not applicable
Base capacity for open-ended piles									
All ZJU-ICL data* (N=13)	0.83±0.35		1.28±0.27	1.07±0.30	1.60±0.32	1.37±0.59	1.42±0.66	2.45±0.46	0.75±0.34
Shaft capacity for piles under compression and tension									
Age Filtered ZJU-ICL Compression piles (N=20)	0.81±0.33	0.51±0.37	0.76±0.28	0.61±0.30	0.71±0.43	0.81±0.48	0.72±0.59	0.81±0.52	Not applicable
Age Filtered ZJU-ICL tension piles (N=24)	0.91±0.24	0.57±0.27	0.96±0.21	0.71±0.23	1.07±0.50	1.07±0.41	0.95±0.68	1.46±0.66	
Shaft capacity for steel and concrete piles									
Age Filtered ZJU-ICL Steel piles (N=34)	0.86±0.26	0.56±0.29	0.89±0.26	0.68±0.26	0.96±0.53	0.98±0.40	0.76±0.62	1.09±0.46	Not applicable
Age Filtered ZJU-ICL Concrete piles (N=10)	0.87±0.39	0.47±0.39	0.81±0.32	0.62±0.32	0.72±0.41	0.86±0.64	1.12±0.63	1.48±0.67	
Base capacity for all piles									
All ZJU-ICL data* (N=32)	0.90±0.45		1.16±.46	1.08±0.45	1.70±0.51	1.33±0.62	1.00±0.92	1.51±0.76	0.75±0.34**

* Two cases in Kikuchi et al (2007) were not included in ZJU-ICL database but used for base capacity assessment only

** Only open-ended piles are counted as HKU end bearing procedure is only applicable to open-ended piles.