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A general load-transfer formulation for the base resistance of large-diameter open-ended pipe piles driven in sand

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ABSTRACT: At the previous symposium, a *new 'unified' CPT-based design method* for estimating the axial capacity of driven piles in sand was introduced. This method has replaced all its predecessors in the design standard ISO/DIS 19901-4:2022. The method estimates both the shaft resistance and the base resistance at a displacement of 10% of the pile diameter. However, when assessing the performance of a foundation, estimating the pile settlement as a function of the applied load is just as important as determining the ultimate bearing capacity. In addition to considering the compressibility of the pile, load-transfer curves for the pile shaft and base are required to estimate this settlement. As general load-transfer curves for the pile base of open-ended pipe piles are lacking, this paper focuses on these. A general load-transfer formulation is presented, adhering to the *new 'unified' CPT-based design method*. The formulation is also evaluated against test data, showing good agreement. Based on this, it is concluded that the base response of large-diameter open-ended pipe piles significantly differs from that of closed-ended piles and require its own formulation.

Keywords: pile response; open-ended pipe piles; compression loading; load-transfer formulation; test results.

1 INTRODUCTION

Load-transfer formulations can be used to estimate the pile displacement as result of a certain loading regime. As foundation piles generally aim to limit displacement under the expected loads, load-transfer formulations are key ingredients in the assessment of pile design. This can be in particular relevant for large diameter piles, since large deformations are needed to mobilise the ultimate pile capacity.

When it comes to assessing axial pile capacity of driven piles in sand, the *new 'unified' CPT-based design method* (Lehane et al., 2020a) can be seen as 'state-of-the-art'. The method is also adopted in ISO 19901-4 (ISO, 2022). This method was developed using a database of high-quality pile load tests. As an extension of the research on axial pile capacity, this 'unified database' was also used for calibration of load-transfer curves (Lehane et al., 2020b). However, it was recognised that representative base response data of open-ended pipe piles is sparse. The reasons mentioned are twofold. First, the need to re-zero strain gauges after installation is mentioned. Secondly, it is mentioned that twin-walled piles are needed to determine the relative contributions of the internal friction, the annular resistance, and the external friction. Ultimately, only data of seven closed-ended piles data was available for the calibration and an hyperbolic equation was derived to estimate the measured base response of these piles. The equation, however, was employed to represent the base response of both closed- and open-ended piles. In combination with a load-transfer function for the pile shaft, the difference between calculated and measured pile head displacement was generally less than 0.5% of the pile diameter at a pile head load of 50% of the ultimate capacity.

However, it is also recognised that the base response of open-ended piles differs from the base response of closed-ended piles. The base capacity of an open-ended pile is made up of the resistance at the annulus and the resistance from the soil plug and the mobilisation of the annular resistance may differ from the mobilisation of the plug resistance (e.g. Han et al., 2020). The greatest similarity to the mobilisation of the base resistance of a driven closed-ended (CE) pile is observed for the mobilisation of the annulus resistance (e.g. Gavin and Lehane, 2007). For piles, driven to their final penetration in a fully/mainly coring mode, what is particularly the case for large diameter piles, it is however expected that the mobilisation of the soil plug resistance shows more similarity to the mobilisation of a non-displacement pile (Lehane and Randolph, 2002). Besides this, the plug will also compress during loading. As a consequence, more pile displacement is required to mobilise the base resistance.

This paper presents a general load-transfer formulation for the base resistance of driven large diameter open-ended pipe piles in sand. The first part of the paper focusses on the derivation of the formulation, whereas the second part consist of an evaluation of the formulation based on test data.

2 DERIVATION OF THE PROPOSED LOAD-TRANSFER FORMULATION

2.1 Typical load-transfer curves for closed ended piles

Typically, load-transfer curves for the pile base are described with hyperbolic functions (e.g. Lehane et al., 2020b). A possible function to estimate the mobilisation of the base stress, q_b, as function of base displacement, s_b, is given by:

$$\frac{q_b}{q_{b;ref}} = \frac{s_b}{R_f \cdot s_b + (1 - R_f) \cdot s_{b;ref}} \qquad (1)$$

where $q_{b;ref}$ is the base stress at the reference base displacement, $s_{b;\mathrm{ref}}$ (typically of 0.1 times the outer pile diameter, D) and R_f the hyperbolic failure ratio.

For driven closed-ended piles, a good match with measured base responses is obtained with $R_f = 0.9$ (e.g. Plantema, 1948; Lehane et al, 2020b), whereas a reasonable estimation of measured base response is obtained with $R_f = 0.7$ for non-displacement piles (e.g. Kruizinga, 1975; Duffy et al., 2024). The softer mobilisation can be attributed to a lower degree of soil displacement, and thus prestressing, during pile installation. Both curves are plotted in Figure 1.

2.2 Plug compression

As mentioned in the introduction, for large-diameter piles, the mobilisation of soil plug resistance is expected to resemble that of a non-displacement pile more than a displacement pile. However, as illustrated in Figure 2, the plug will compress during loading, resulting in plug base displacements smaller than s_b. This affects the mobilisation of soil resistance beneath the pile. In order to estimate the plug compression, (i) the stress acting on the soil plug, (ii) the stress distribution in the soil plug, and (iii) the compressibility of the soil plug should be estimated.

The stress acting on the soil plug, q_{plug}, can be estimated by reducing the CPT cone resistance, q_c, by means of a reduction factor α:

$$q_{plug} = \alpha \cdot q_c \qquad (2)$$

To quantify the effects of plug compression on the mobilisation of q_{plug}, a hypothetical open-ended pipe pile with an infinitely thin wall, which does not contribute to any resistance, is considered. For an incompressible plug, the mobilisation of q_{plug} is assumed to be similar to the mobilisation of q_b for a non-displacement pile (Eq. [1] with $R_f = 0.7$). The value of q_{plug} at $s_b = 0.1D$ is estimated with $\alpha = 0.25$, based on studies by Kruizinga (1975) and Gavin et al. (2013). This curve is given in Figure 3 (incompressible plug).

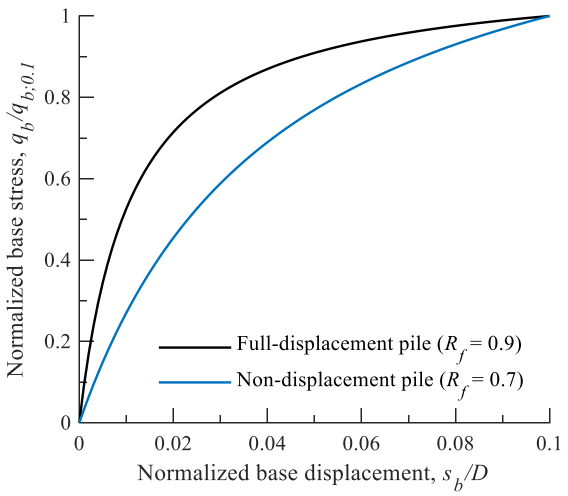

Figure 1. Typical base load-transfer curves for closed-ended piles.

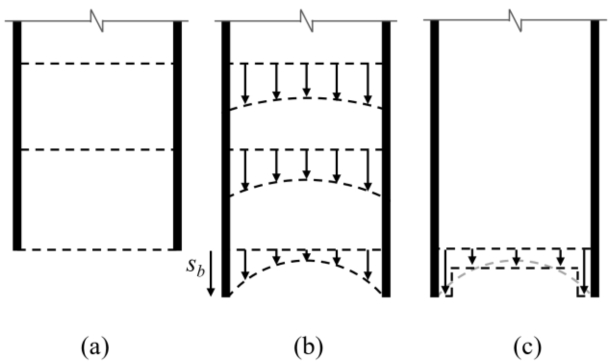

Figure 2. Schematization of the plug displacements during static loading: (a) initial positions, (b) after loading and (c) simplification of the displacements at the pile base.

The stress distribution in the soil plug, $\sigma'_{v;plug}$, as function of the distance to the pile base, h, can be estimated using Terzaghi's method on arching in ideal soils (1943):

$$\sigma'_{v;plug}(h) = q_{plug} \cdot e^{-\left(\frac{4 \cdot \beta}{D_i} \cdot h\right)} \qquad (3)$$

where β is the limiting friction ratio and D_i is the inner pile diameter (Lehane and Randolph, 2002).

To quantify the effects of plug compression, a one-dimensional finite element model is employed, using the *Hardening Soil Model*, which accounts for stress-dependent compressibility. Four scenarios are considered to obtain representative plug compressions: two relative densities, D_r, and two initial vertical effective stress levels, σ'_{v0}. For each scenario, the q_c value is estimated based on the correlation found by Lunne and Christoffersen (1983) and the *Hardening Soil Model* parameters are sourced from Brinkgreve et al. (2010). Table 1 provides an overview of the four scenarios and their corresponding parameters, where $E_{oed;ref}$ is the reference stiffness at 100 kPa and m is the exponent expressing the stress dependence of the stiffness. All four scenarios are considered using limiting friction ratios, β, of 0.28 and 0.55, leading to eight calculations in total.

Table 1. Considered scenarios for quantifying the effect of plug compression.

Scen.	D_r (%)	σ'_{v0} (kPa)	q_c (MPa)	$E_{oed;ref}$ (MPa)	m (-)
1	60	200	15	41	0.51
2	60	400	25	41	0.51
3	90	200	36	59	0.42
4	90	400	59	59	0.42

Figure 3 presents the plug stress as function of s_b. The results of four calculations are included, representing the lowest and highest q_c values. The curve for the incompressible plug serves as the reference case. The figure indicates that as the plug compresses, more pile base displacement, s_b, is required to mobilise the plug stress. Both lower β values and higher q_c values result in increased plug compression.

For implementation in the proposed load transfer formulation, the derived curves are normalised by the plug stress at $s_b = 0.1D$, $q_{plug;0.1}$. Figure 4 presents the bandwidth of all calculation results. For convenience, these results are approximated using the hyperbolic function given by Eq. [1]. For $\beta = 0.28$ and $\beta = 0.55$, the curves are reasonably described with $R_f = 0.3$ and $R_f = 0.5$, respectively.

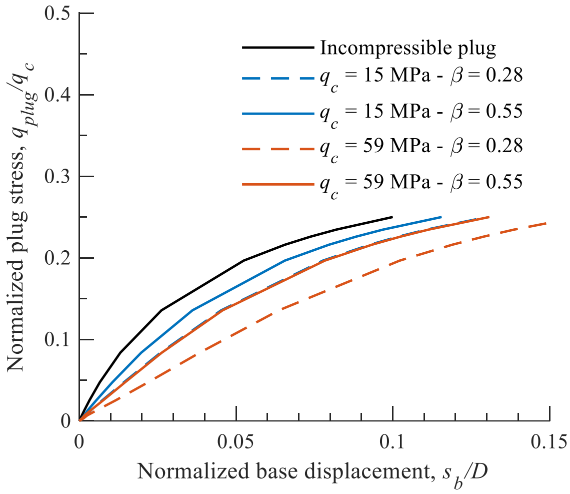

Figure 3. Derived relation between plug stress and pile base displacement for different scenarios.

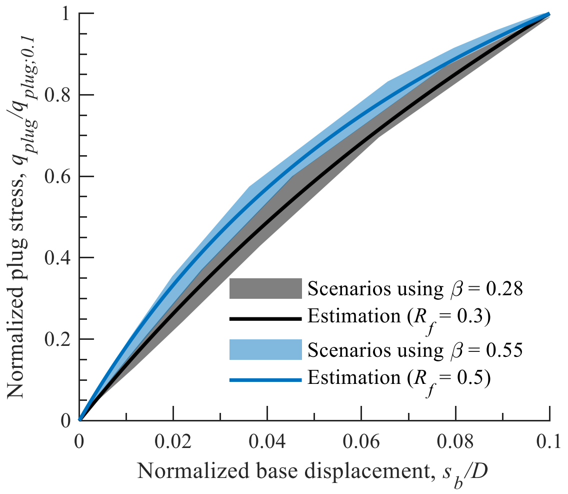

Figure 4. Derived load-transfer curves based on fictive open-ended pipe piles with different plug compression.

3 PROPOSED LOAD-TRANSFER FORMULATION

For a proper description of the mobilisation of the base resistance open-ended pipe piles, a distinction should be made between the annular resistance and the plug resistance. As the *new 'unified' CPT-based design method* combines these two contributions, it is useful to define a load-transfer that respects this approach. The average base stress, q_b, at a certain base displacement can be described as:

$$q_b = q_{b;e} * A_{re} + q_{plug} * (1 - A_{re}) \quad (4)$$

where A_{re} is the effective area ratio, $q_{b;e}$ is the stress acting on the 'effective area' and q_{plug} is the stress acting on the remaining plug area.

For piles driven in a fully or mainly coring mode, it is assumed that the 'effective area' is fully located in the outer ring of the base area, referred to as the 'effective outer ring'. This is illustrated in Figure 2(c). Additionally, for piles with a low effective area ratio ($A_{re} \leq 0.30$), it is assumed that the mobilisation of the two identified resistances can be described independently and combined through superposition. And finally, it is assumed that the displacement required to mobilise the resistance acting on the 'effective outer ring' is proportional to its thickness rather than the full pile diameter. These assumptions have led to the following equations:

$$\frac{q_{b;e}}{q_{b;e;ref}} = min\left(1, \frac{s_b}{R_{f;e} \cdot s_b + (1 - R_{f;e}) \cdot s_{b;e;ref}}\right) \quad (5)$$

with $R_{f;e} = 0.9$ (similar to driven CE piles) and a reference displacement $s_{b;e;ref}$ equal to 0.1 times the 'effective wall thickness', t_e, defined as:

$$t_e = D \cdot (1 - [1 - A_{re}]^{0.5}) \quad (6)$$

The mobilisation of the stress acting on the remaining plug area, q_{plug}, is described by:

$$\frac{q_{plug}}{q_{plug;ref}} = \frac{s_b}{R_{f;plug} \cdot s_b + (1 - R_{f;plug}) \cdot s_{b;ref}} \quad (7)$$

According to the *new 'unified' CPT-based design method*, at the reference displacement $s_{b;ref}$ equal to $0.1D$, $q_{b;e;ref} = 0.5 \cdot q_c$ and $q_{plug;ref} = 0.12 \cdot q_c$. Based on section 2.2, $R_{f;plug}$ is expected to range from 0.3 to 0.5. Figure 5 illustrates the load-transfer functions derived from the above equations, including the hyperbolic curve for a driven CE pile, as derived by Lehane et al. (2020b). For open-ended piles with a low A_{re}, the proposed load-transfer formulation results in a relatively stiff initial base response. This can be explained by the small displacement required to mobilise the resistance on the 'effective outer ring.' However, once this resistance is fully mobilised, a clear transition to a much softer response is observed.

4 COMPARISON WITH TEST RESULTS

To evaluate the proposed base load-transfer formulation, calculated responses are compared with responses derived from static load tests. In the absence of test data for low-A_{re} double-walled piles, test data from single-walled piles is used for the evaluation. Data from two test campaigns in The Netherlands are selected. First, the derived base responses presented in

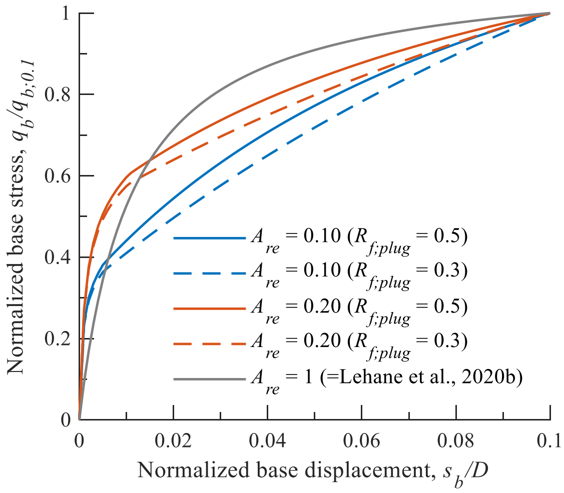

Figure 5. Results generated with the proposed base load-transfer formulation.

De Lange et al. (2025) are considered. Secondly, the data from the EURIPIDES project (Fugro, 1996) are re-analysed.

Table 2 presents some characteristics of the selected pile load tests, where *t* represents the wall thickness and *L* denotes the embedment length. In the EURIPIDES test programme (Eemshaven), one single pile was installed at two locations and load tested at multiple depths. The load tests were performed displacement controlled (1 mm/min) up to base displacement of about 0.2 times *D*. All virgin compression load tests are selected for the evaluation. In the test programme presented in De Lange et al. (2025), four piles were installed to different depths on the Maasvlakte 2. The load tests were performed load controlled, including 1-hour creep periods, up to a base displacement of 0.1 times *D*. The strain data from both test campaigns included residual strains after pile installation.

Table 2. Characteristics of the selected tests.

Location	q_p (MPa)	*D* (mm)	*T* (mm)	*L* (m)
Eemshaven	50-60	763	35.6	30-47
Maasvlakte 2	14-52	1220	16.0	33-38

For both test campaigns, the same method is used to approximate the base response. The initial step involves analysing the axial force along the pile length, measured under different loads. As larger base displacements occur, internal friction becomes dominant over external friction. This allows for the derivation of a β value that represents the internal plug stresses. For the EURIPIDES project, internal total stress measurements were also available, which substantiate this approach. Subsequently, a level can be identified at which the plug stresses become negligible. Finally, the base stress is approximated based on the axial force at this level. This is achieved by reducing this force with the friction acting on the external pile wall below that level. The external friction was approximated by using the *new 'unified' CPT-based design method.*

Figure 6 and 7 show the base stress-base displacement responses as derived from the test data and as simulated by the proposed load-transfer formulation. For all cases, the measured final filling ratio (*FFR*) is used to calculate A_{re}, which ranges from 0.06 to 0.26. Further, as different β values were derived from the test results (about 0.25 for the Eemshaven pile and about 0.55 for the Maasvlakte piles), different $R_{f;plug}$ values are used. Both the A_{re} and the $R_{f;plug}$ values are included in the figures. For comparison, the hyperbolic function derived by Lehane et al., (2020b), representing the response of a driven CE pile, is also given in the figures.

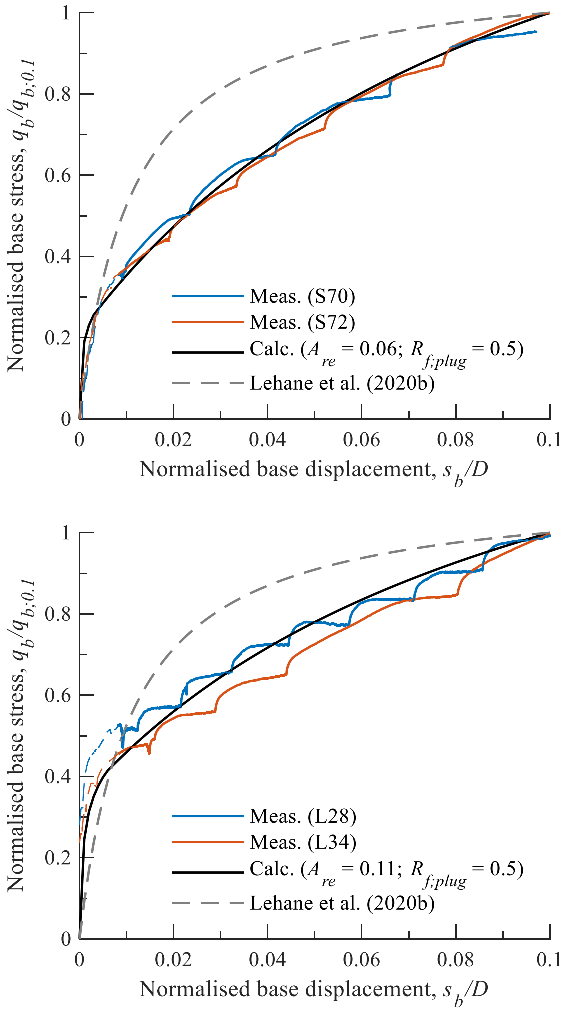

Figure 6. Base responses as derived from Maasvlakte 2 test data and as simulated by load-transfer formulations.

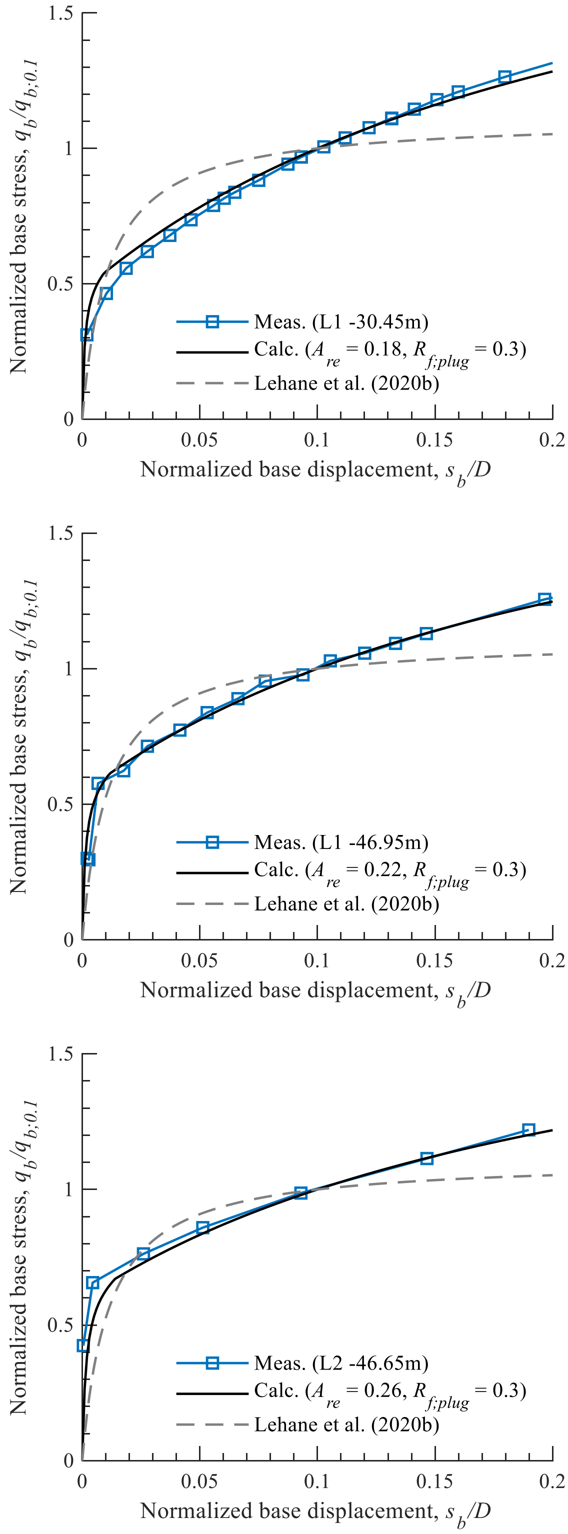

Figure 7. Base responses as derived from EURIPIDES test data and as simulated by load-transfer formulations.

It is concluded that the proposed load-transfer formulation provides an accurate description of the measured base response and a significant improvement over the hyperbolic function representing a driven closed-ended pile.

5 CONCLUDING REMARKS

A general load-transfer formulation for the base resistance of large diameter open-ended pipe piles driven in sand is derived and evaluated with test data. Superposition of the individual contributions of the annular and plug resistance is proposed for piles which are driven in a (mainly) coring mode that fulfil $A_{re} \leq 0.3$. Data from two test campaigns show strong agreement with the derived load-transfer formulation. The base response of large-diameter open-ended piles significantly differs from that of closed-ended piles.

AUTHOR CONTRIBUTION STATEMENT

D.A. de Lange: Methodology, Validation, Visualization and Writing – original draft. **H.J Lengkeek**: Methodology, Validation and Writing – review & editing. **K.G. Gavin**: Supervision.

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