Delft University of Technology

Document Version
Final published version

Licence
CC BY-NC-ND

Citation (APA)
Argyroulis, K., Putteman, J., Gavin, K., & Roubos, A. A. (2024). Pile driveability predictions of open ended tubular piles in sand using the Unified Method. In N. Guerra, M. Matos Fernandes, C. Ferreira, A. Gomes Correia, A. Pinto, & P. Sêco e Pinto (Eds.), *Proceedings of the XVIII ECSMGE 2024: Geotechnical Engineering Challenges To Meet Current And Emerging Needs Of Society* (pp. 2076-2080). Article 391 CRC Press / Balkema - Taylor & Francis Group. https://doi.org/10.1201/9781003431749-391

Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-391

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Pile driveability predictions of open ended tubular piles in sand using the Unified Method

Prédictions de la conduite des pieux tubulaires à extrémité ouverte dans le sable dense selon la méthode unifiée

K. Argyroulis[*]
SBE Engineering Consultants, Rotterdam, The Netherlands

J. Putteman
SBE Engineering Consultants, Sint-Niklaas, Belgium

K. Gavin
Civil Engineering and Geosciences, TU Delft, Delft, The Netherlands

A.A. Roubos
Civil Engineering and Geosciences, TU Delft, Delft, The Netherlands;
Port of Rotterdam Authority, Rotterdam, The Netherlands

[*]*konstantinos.argyroulis@sbe-engineering.nl*

ABSTRACT: In this study, driving records of 18 open-ended steel tubular piles installed in dense sandy soil conditions at five sites in the Netherlands were utilized to evaluate models that are currently used in practice for predicting the static soil resistance during driving (SRD), as well as a recently developed method, known as the Unified Method. Since the Unified Method is a static axial capacity-CPT-based design method, slight modifications to the originally proposed formulas were examined to allow estimation of the SRD. This paper presents a modified format of the Unified Method and its performance is assessed by comparing predicted with measured hammer blow count profiles. It is eventually shown that the modified Unified Method leads to overall improved blow count predictions compared to current approaches.

RÉSUMÉ: Dans cette étude, les enregistrements de battage de 18 pieux tubulaires en acier à extrémité ouverte installés dans des conditions de sol sableux denses sur cinq sites aux Pays-Bas ont été utilisés pour évaluer les modèles actuellement utilisés dans la pratique pour prédire la résistance statique du sol pendant le battage (SRD), ainsi qu'une méthode récemment développée, connue sous le nom de méthode unifiée. Étant donné que la méthode unifiée est une méthode de conception basée sur la capacité axiale statique CPT, de légères modifications des formules initialement proposées ont été examinées pour permettre l'estimation du SRD. Cet article présente un format modifié de la méthode unifiée et ses performances sont testées en comparant les profils de nombre de coups de marteau prédits et mesurés. Il est finalement démontré que la méthode unifiée modifiée conduit à des prévisions globalement améliorées du nombre de coups par rapport aux approches actuelles.

Keywords: Pile driveability; SRD; Unified Method.

1 INTRODUCTION

The driving process is commonly assessed by utilizing commercially available pile driveability software that are based on 1-D wave equation analysis. These enable the modelling of the hammer – pile – soil system as a series of masses and springs and simulate the stress wave phenomena during the installation process.

The total soil resistance consists of both a static and a dynamic component and is usually represented by elasto-plastic springs with dashpots at the toe and around the pile shaft area. The static component, also referred to as SRD (static resistance during driving), represents the cumulative increase of shaft resistance with further pile penetration, and the toe resistance associated with each driving increment (Prendergast et al (2020)). The dynamic component is typically quantified by damping factors (Schneider et al (2010)) that depend on soil type and is expressed as function of the SRD.

This paper examines the applicability of the Unified Method (Lehane et al (2020)) in driveability predictions. The Unified Method is a CPT-based static axial capacity design method for driven piles in silica sand. This design approach is included in the 2022 edition of ISO-19901-4 replacing the four CPT methods (ICP-05, Fugro-05, NGI-05 and UWA-05).

Since SRD differs from pile axial capacity in terms of consolidation, stress equalization, and time effects (Schneider et al (2010), Byrne et al (2018), Prendergast et al (2020)) modifications are required to allow estimation of SRD. The modifications applied to the Unified Method are inspired by the ones proposed by Byrne et al (2018) and Prendergast et al (2020) that were successfully applied at very similar axial capacity design methods (ICP-05, UWA-05) for estimation of the SRD, leading to improved driveability predictions.

A common and practical way to assess the pile driving resistance using specific hammering equipment, is through the number of required hammer blows per 25 cm increment of penetration. Utilizing as input to the driveability model the impact hammer energy record of 18 open-ended tubular piles driven in mainly dense sand conditions at 5 sites in the Netherlands, an assessment of the modified Unified Method is made as well as a comparison with frequently used in practice SRD models in terms of predicted against measured hammer blows per 25cm.

2 MODIFIED UNIFIED METHOD

Analytical explanation of the Unified Method and of the formulas used to calculate the shaft and toe capacity can be found in Lehane et al (2020). The following sections provide the modifications that were applied to this method, which can also be found in detail in the Master Thesis by Argyroulis (2022). Section 2.3 provides the formulas of the modified Unified Method.

2.1 Modified shaft resistance

The Unified CPT-based Method was calibrated using the 'Unified database' (Lehane et al (2017)) comprising 71 static pile load tests in siliceous sand deposits with diameters between 300 and 800 mm. As explained in Lehane et al (2020), the shaft capacity of driven piles in sand increases with time over a period of about one year and the Unified Method was calibrated to estimate the shaft capacity at around 14 days after driving. Therefore, the shaft resistance during driving will be lower than the shaft capacity currently estimated by this approach.

Jardine et al (2006) interpretation of Intact Ageing Curves of piles installed in the Dunkirk (France) dense sand revealed that the shaft capacity 1 day after driving was approximately 70% of the shaft resistance estimated with the ICP-05 method (10-30 days after installation). Lehane et al (2017), included records from piles installed in dense sand at Blessington (Ireland) and Lavrik (Norway) and derived the following time factor (best fit line – (1)) that can be applied when using the pile capacity methods: API-00, ICP-05, UWA-05, Fugro-05 and NGI-05:

$$F_{time} = \frac{1}{exp(-0.1 * t^{0.68}) + 0.45} + d_{offset} \qquad (1)$$

where t (days) after installation and d_{offset} (-) an offset value depending on the method used.

Setting the offset and time to zero a factor of about 0.7 is obtained. By using a time factor of 0.7, Byrne et al (2018) and Prendergast et al (2020) showed improved driveability predictions when using the ICP-05 and UWA-05 methods. Due to great similarity of the aforementioned CPT based design methods (API-00, ICP-05, UWA-05, Fugro-05 and NGI-05) with the Unified Method, 70% of the shaft capacity predicted with this method is considered to be a reasonable estimation of the shaft resistance mobilized during driving.

2.2 Modified toe resistance

The original toe resistance formulation cannot be directly used for pile driveability predictions since the base resistance estimated, is the one mobilized at pile tip displacements equal to 10% the pile diameter. In normal driving conditions though, the pile will only displace a few mm per hammer blow. Thus, for driveability analysis, it is required to define the maximum toe resistance that corresponds to the assumed quake value (displacement at yield). Signal matching analyses of dynamic driving data indicate quake values of about 2.5 mm for both the shaft and toe resistances.

Due to its simplicity the recommended by API (2000) tip load-displacement model (Table 1) was used in this case to derive an appropriate toe resistance mobilized during driving.

*Table 1. Pile tip-load-displacement (Q-z) curve (*API (2000)*).*

$\frac{w_b}{D}$	$\frac{q_b}{q_{b0.1}}$
0.002	0.25
0.013	0.5
0.042	0.75
0.073	0.9
0.1	1

where w_b represents the base displacement (mm), D is the pile diameter (mm), $qb_{0.1}$ is the mobilized toe resistance at 10% the pile tip displacement (kPa), and q_b (kPa) the mobilized toe resistance at w_b tip displacement. Utilizing the original formula of toe resistance of the Unified Method and a quake value of

2.5 mm, the mobilized q_b driving toe resistance can be determined.

Based on Table 1, equation (10) was developed to match the tabulated API base displacement response with the addition of an extra term used to account for residual loads (q_{res}) after a hammer blow. While Paik et al (2003) measured that residual stresses were in the range of 11-14% of the CPT qc value for 356 mm (diameter) open and closed-ended piles in dense sand, Byrne et al (2018)_suggested values 1-10% of the qc in medium dense sands for large offshore steel open-ended monopiles. Clearly, there is an uncertainty on the residual loads, and thus a 10% of the $qb_{0.1}$ was used in the following case studies presented.

2.3 Formulas of modified Unified Method

Below the modified formulas of the Unified Method that can be used to estimate the SRD are presented.

Shaft resistance

$$Q_{shaft} = \pi * D * \int_0^L \tau f_{SRD} dz \tag{2}$$

$$\tau f_{SRD} = F_{time} * (\sigma'_{rc} + \Delta\sigma'_{rd}) * tan\delta_f \tag{3}$$

$$\sigma'_{rc} = \frac{q_c}{44} * A_{re}^{0.3} * \beta \tag{4}$$

$$\beta = \left[\max\left(1, \frac{h}{D}\right)\right]^{-0.4} \tag{5}$$

$$A_{re} = 1 - PLR * \left(\frac{D_i}{D}\right)^2 \tag{6}$$

$$PLR = \tanh\left[0.3 * \left(\frac{D_i}{D_{CPT}}\right)^{0.5}\right] \tag{7}$$

$$\Delta\sigma'_{rd} = \left(\frac{q_c}{10}\right) * \left(\frac{q_c}{\sigma'_v}\right)^{-0.33} * \left(\frac{D_{CPT}}{D}\right) \tag{8}$$

where:

τf_{SRD}	unit shaft resistance (kPa)
D	outer pile diameter (m)
D_i	inner pile diameter (m)
D_{CPT}	CPT cone diameter, 0.0357 m
F_{time}	time factor, 0.7 (-)
σ'_{rc}	radial effective stress (kPa)
β	fatigue factor (-)
h	distance of soil horizon from pile tip (m)
$\Delta\sigma'_{rd}$	increase in radial effective stress (kPa)
δ_f	constant volume friction angle, 29°
A_{re}	effective area ratio (-)
PLR	plug length ratio (-)

Toe resistance

$$Q_b = q_{b_{SRD}} * \pi * \frac{D^2}{4} \tag{9}$$

$$qb_{SRD} = 2.23 * \left(\frac{w_b}{D}\right)^{0.347} * q_{b0.1} + q_{res} \tag{10}$$

$$q_{b0.1} = (0.12 + 0.38 * A_{re}) * qc \tag{11}$$

$$q_{res} = 0.1 * q_{b0.1} \tag{12}$$

3 REMARKS ON MODIFIED UNIFIED METHOD

Some important notes regarding the modified and original Unified Method are summarized below.

With respect to the shaft resistance, the one calculated by equation (3) represents the shaft resistance developed at the external shaft area of the pile. Other SRD models, like the Alm & Hamre (2001) which is used for comparison in the case studies below, incorporate the internal shaft resistance to the external shaft formulation of open-ended piles, while the toe resistance is acting on the pile tip annular area. Contrary to these models, the Unified Method accounts for the internal shaft resistance (plug resistance) to the toe resistance formulation (equation (9)). In that sense it can be expected that for large offshore piles the (modified) Unified Method will predict lower (external) shaft resistance compared to the (external and internal) shaft resistance of Alm & Hamre (2001) model, while the opposite occurs for toe resistance since the modified Unified Method is applied at the gross pile base area, taking into account as well the (inner shaft resistance) plug resistance. This will eventually result in a similar estimation of SRD.

Furthermore, it should be noted that the shaft resistance of the (original) Unified Method considers variation of τf with the degree of soil displacement imparted during driving. This is quantified, as explained in Lehane et al (2020), with the effective area ratio A_{re} that represents the ratio of the soil volume displaced during installation to the pile total volume and the plug length ratio, PLR. Therefore, the original formulas are not only applicable to fully coring cases, but also to partially plugged piles ($PLR < 1$) or even to close ended piles ($A_{re} = 1$). Although the modified version is basically 70% (time factor) of the original shaft resistance, this paper evaluates only fully coring cases, while it would be interesting in the future to assess the performance of the modified Unified Method for closed-ended or partially plygged piles.

Finally, it is mentioned for the modified toe resistance that formula (10) allows the calculation of the maximum driving toe resistance for any quake value chosen (e.g., w_b based on specific project data), while the residual load used requires further research.

4 CASE STUDIES

The detailed analysis of the 18 open-ended piles can be found in (Argyroulis (2022)). In this section, the hammer blow count post-predictions of 5 open-ended piles from 5 locations (Port of Rotterdam, Eemshaven) in the Netherlands are presented (Figure 1, Figure 2, Figure 3). The modified Unified Method is denoted as UM (2020) SRD. It is stated that the piles of APM, RWG, SIF and HHTT terminals (Port of Rotterdam) were partially driven by a vibratory hammer (not examined in this paper), and later on the target depth was reached using hydraulic and diesel impact hammers. It is mentioned that the impact hammer energy was recorded during installation and was used as input into the driveability model, so that the outcome is mainly affected by the chosen SRD model. The results of the UM (2020) SRD are mainly compared to the most frequently used Alm & Hamre (2001) model, while for APM and RWG terminals, predictions were also made with the Stevens et al (1982) model. The AllWave-PDP driveability software was used for the purposes of this study.

5 CONCLUSIONS

Although this study is limited to pile diameters of 1.4 m (APM, RWG, SIF, HHTT terminals) and 0.76 m (EURIPIDES) it can be seen that the Unified Method, when slightly modified is capable of reproducing the hammer blows during installation. A way to assess the predictions made by the SRD models and the actual blow counts measured is through the Mean Absolute Percentage Error (MAPE) as a measure of average deviation between predicted and measured values. It was observed that the modified Unified Method has less deviation from the actual record of blows counts than the Alm & Hamre (2001) model in 13 out of 18 cases, whereas in 3 cases (out of 18) the modified Unified Method showed a slight over-under prediction, and in the remaining 2, both models showed the same deviation (Argyroulis (2022)). Despite that, the Alm & Hamre (2001) model is still very reliable model as can be seen in the figures below. The Stevens et al (1982) model, although it is a very practical and easy to use model, since it doesn't consider friction fatigue it tends to overpredict the number of blows (e.g., RWG terminal, Figure 1).

Further research is required to investigate the appropriate diameter range for which the modified Unified Method can be used, as well as variation in soil conditions (e.g., inclusions of soft clay layers).

Finally, the importance of collecting high quality driving records should be highlighted as the only way to improve the efforts made for more reliable driveability predictions, which may lead to minimization of installation risks and construction delays.

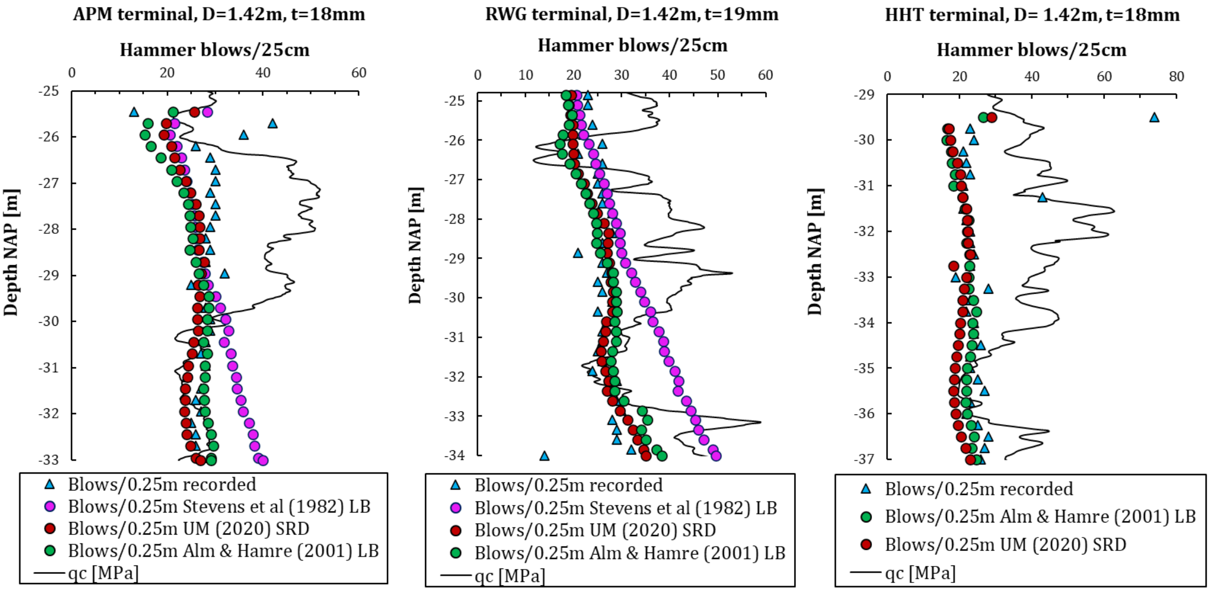

Figure 1. Post driveability predictions of hammer blow count profiles for terminals APM, RWG and HHTT at Maasvlakte, Rotterdam. Hydraulics hammers IHC S-200, IHC SC-200 and IHC S-280 were used.

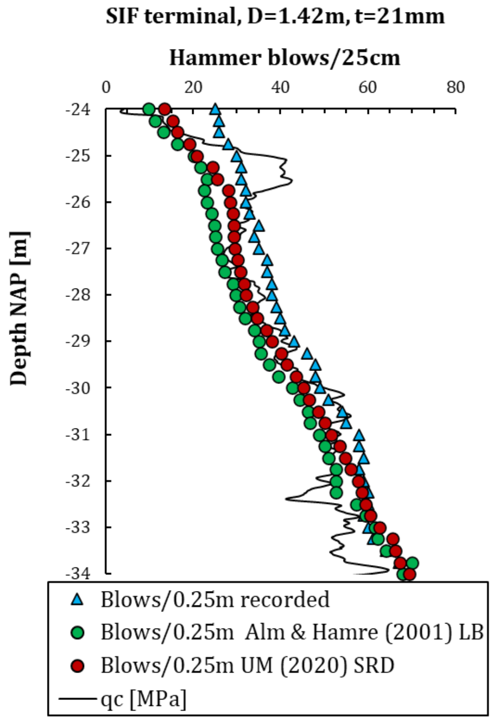

Figure 2. Post-predicted blow count profile for SIF terminal at Maasvlakte, Rotterdam. A Delmag D100-13 diesel hammer was used.

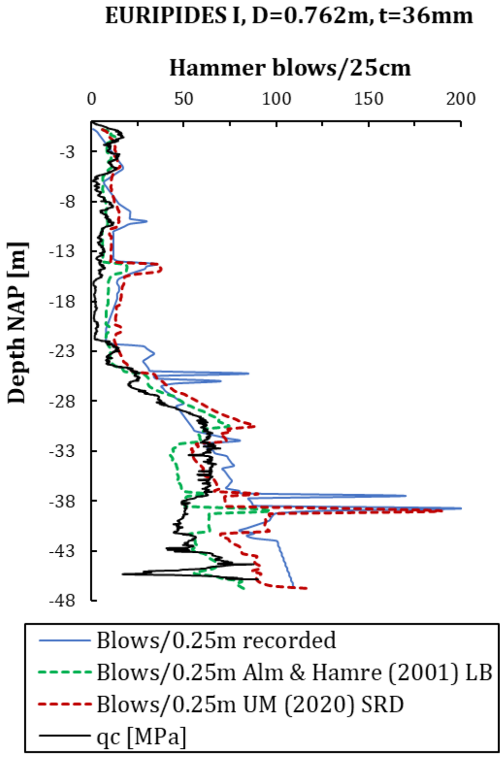

Figure 3. Post-predicted blow count profile for EURIPIDES project at Eemshaven. A IHC S-90 hydraulic hammer was used.

REFERENCES

Allnamics, AllWave-PDP, Driveability Software for Impact Driving, Available at: https://allnamics.com/en/portfolio-posts/allwave-pdp-driveability-software-for-impact-hammers/.

Alm, T., Hamre, L. (2001). Soil Model for Pile Driveability Predictions Based on CPT Interpretations. *Proceedings of the 15th International Conference on Soil Mechanics and Foundation Engineering,* Istanbul, Turkey, pp. 1297–1302.

API (2000). API RP2A-WSD, Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms–working Stress Design, American Petroleum Institute, Washington, DC.

Argyroulis, K. (2022). *Performance of steel open ended pile driveability prediction methods in dense sand*, Master Thesis, Delft University of Technology. Available at: http://resolver.tudelft.nl/uuid:bb85aefa-bd35-4c1d-90b3-1a5788d91050.

Byrne T., Gavin, K., Prendergast L.J., Cachim, P., Doherty P. and Pulukul S.C. (2018). Performance of CPT-based methods to assess monopile driveability in North Sea sands, *Ocean Engineering*, 166, pp.76-91, https://doi.org/10.1016/j.oceaneng.2018.08.010.

Jardine, R., Standing, J., Chow, F. (2006). Some observations of the effects of time on the capacity of piles driven in sand, *Geotechnique*, 56, pp.227–244, https://doi.org/10.1680/geot.2006.56.4.227.

Lehane, B.M., Lim, J.K., Carotenuto, P., Nadim, F., Lacasse, S., Jardine, R., van Dijk, B.F.J. (2017). Characteristics of Unified Databases for Driven piles, *Offshore Site Investigation Geotechnics 8th International Conference Proceedings*, London, UK, 1, pp.162-194, https://doi.org/10.3723/OSIG17.162.

Lehane, B., Liu, Z., Bittar, E., Nadim, F., Lacasse, S., Jardine, R. J., Carotenuto, P., Jeanjean, P., Rattley, M., Gavin, K., Haavik, J., & Morgan, N. (2020). A New 'Unified' CPT-Based Axial Pile Capacity Design Method for Driven Piles in Sand, In *Proceedings of the 4th International Symposium on Frontiers in Offshore Geotechnics*: *American Society of Civil Engineers*, pp.463-477.

Paik, K., Salgado, R., Lee, J., Kim, B. (2003). Behavior of open- and closed-ended piles driven into sands. *Journal of Geotechnical and Geoenvironmental Engineering*, 129, pp.296–306. https://doi.org/10.1061/(ASCE)1090-0241(2003)129:4(296).

Prendergast, L.J., Gandina, P., Gavin, K. (2020). Factors Influencing the Prediction of Pile Driveability Using CPT-Based Approaches, *Energies,* 13(12), [3128]. https://doi.org/10.3390/en13123128.

Schneider, J., Harmon, I. (2010). Analyzing drivability of open ended piles in very dense sands, *DFI Journal - The Journal of the Deep Foundations Institute*., 4(1), pp.32–4, https://doi.org/10.1179/dfi.2010.003.

Stevens, R., Wiltsie, E., Turton, T.(1982). Evaluating drivability for hard clay, very dense sand, and rock, *Offshore Technology Conference,* Houston, USA, https://doi.org/10.4043/4205-MS.