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Evaluation of the 'Unified' CPT-based axial pile capacity design methods for driven piles in clay using new case studies

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ABSTRACT: The new 'Unified' CPT-based method for estimating the axial capacity of driven piles in clay was proposed by Lehane et al (2022). The method was developed through a Joint Industry Project (JIP), which led to the creation of a 'Unified' database of high-quality pile load tests in sand and clay. This database is approved by key representatives from multiple organisations across the offshore energy sector. The method for clay was developed during the second phase of the JIP, after the establishment of a 'Unified' method for sands. This paper demonstrates how the method performs in practice for a variety of real-life offshore clay profiles published by the industry. Results are compared with those from other common methods, such as the original API "alpha" method, the modified NGI "alpha" method including the effects of plasticity and the effective stress UWA and Fugro methods. The focus is on soil profiles dominated by clay layers; however, some interlayered profiles are also included to show how the sand and clay methods perform in tandem for typical offshore project soil profiles. Key differences between the results from these methods are discussed, and the applicability of the unified method for pile design in clay evaluated.

Keywords: driven piles; clay; cone penetration tests; unified method.

1 INTRODUCTION

The popularity of the Cone Penetration Test (CPT) and the similarity between the mode of penetration of a cone and driven pile have provided strong motivation in the search for direct correlations between the CPT tip resistance and the axial pile capacity (Lehane et al, 2022a). The four most widely used CPT methods for offshore driven pile design were those recommended by the API (2011) guidelines. More recently, CPT-based methods to calculate the axial capacity in sand (Lehane et al., 2020) and clay (Lehane et al. 2022) were developed through a Joint-Industry-Project. These methods were developed based on a reconciled database of pile tests. These methods are commonly referred to as the "Unified methods" to communicate the fact that it was developed through consensus across a wide group of researchers and practitioners from the field of offshore geotechnical engineering. The method for sand has recently been included in ISO recommendations in the main text and the method for clays in included in an informative annex. This paper provides case studies where the unified method for clay has been applied to clay from offshore locations around the world. Results using the unified method are compared to results using the methods previously included in API (2011). The case studies make use of published CPT data from locations with significant offshore clay deposits around the world. An open-ended pile of 1 m diameter and 50 mm wall thickness is used as a reference case for axially loaded piles. The objective is to understand how the unified CPT method performs relative to the other methods in predominantly clay soil profiles in order to demonstrate experience and support adoption of the unified method as a standard design method.

2 METHOD

The unified method was calibrated using a database of 71 sand and 49 clay high-quality pile load tests (Lehane et al., 2017), mostly from onshore sites. The skin friction is given by:

$$\tau_f = 0.07 F_{st} q_t Max[1, (h/D^*)]^{-0.25}$$
$$where\ F_{st} = 1\ for\ clays\ in\ Zones\ 2, 3, and\ 4, and$$
$$F_{st} = 0.5 \pm 0.2\ for\ Zone\ 1\ clays$$

Zones refer to soil behavior typ (SBT) by Robertson (2009). End bearing is given by:

$$q_{b0.1} = 0.8 q_t\ (closed\ ended\ piles)$$
$$q_{b0.1} = 0.4 q_t\ (open\ ended\ piles)$$

Tests in the database were limited to piles with a minimum diameter of 200 mm and a minimum embedment length of 5 m. In the present work, the unified CPT method is applied to a set of example piles and then compared to results from the main text method of API (2011) and the NGI 2005, Fugro 2005 and UWA 2005 CPT-based methods as included in API (2011). The ICP method is not included due to the soil data being limited to CPT data only.

Although the piles are hypothetical, the analyses use real CPT data previously published by NGI and Fugro.

2.1 Location classification

The following criteria are used to classify each analysis case:

1. If the proportion of the pile length in clay soils exceeds 70%, then those piles are categorized as “piles in clay”.
2. If the proportion of the pile length in sand soils exceeds 70%, then those piles are categorized as “piles in sand”.
3. If the proportion of the pile length in both sand and clay soils are between 30% to 70%, then those piles are categorized as “piles in interlayered soil”.

All examples included herein are categorised as clay locations. The first two criteria are consistent with those followed by Lehane et al. (2017) to identify sand profiles and clay profiles. It should be noted that the classification of a pile at locations with layered soil profiles can change depending on the length of embedment.

2.2 Soil profiles

Clay profiles have been assembled from literature where offshore CPT records have been included. One relevant onshore record from a marine clay deposit is also included. The use of published soil data allows calculation of pile capacity on a variety of profiles independent of project choices to develop a specific foundation type. Profiles from a diverse set of locations are used, with the majority from offshore Europe, representing various geological settings. Furthermore, profiles from the Gulf of Mexico and the East China Sea demonstrate how the methods perform in different offshore regions. The geographical distribution and range of water depths are listed in Table 1. The q_t profiles from each location are shown in Figure 1.

2.3 Pile dimensions

The analyses were performed using a hypothetical pile with a diameter of 1 m, a wall thickness of 50 mm, and embedment length that ranged from 15 m to 40 m depending on the depth of the clay

Table 1 The analysed Soil profiles and respective sources of data

no	Area	Description	Reference
1	Norwegian sea 1300 m depth Luva	Very Soft to Stiff clay, I_p 30 – 50 %, OCR falling from 3 to 1.	Lunne et al,. (2013)
2	Norwegian sea 350 m depth Skarv	Soft to stiff, low plasticity, sandy clays with frequent inclusions of gravel.	Langford et al. (2012)
3	Onshore marine clay Onsøy	Lightly overconsolidated onshore clay of marine deposition	L‘heureux et al. (2017)
4	North sea shallow site DONG 1	Layered profile with layer of normally to lightly overconsolidated clay	Liu et al. (2020)
5	East China sea Zhuanghe	Very low strength Clay and silty clay	He et al (2022)
6	Gulf of Mexico Mad Dog	Uniform soft to stiff plastic clay	Schroeder et al. (2006)
7	North Sea Windfarm	Overconsolidated clay with layers of sand and transitional material	Teng et al. (2022)

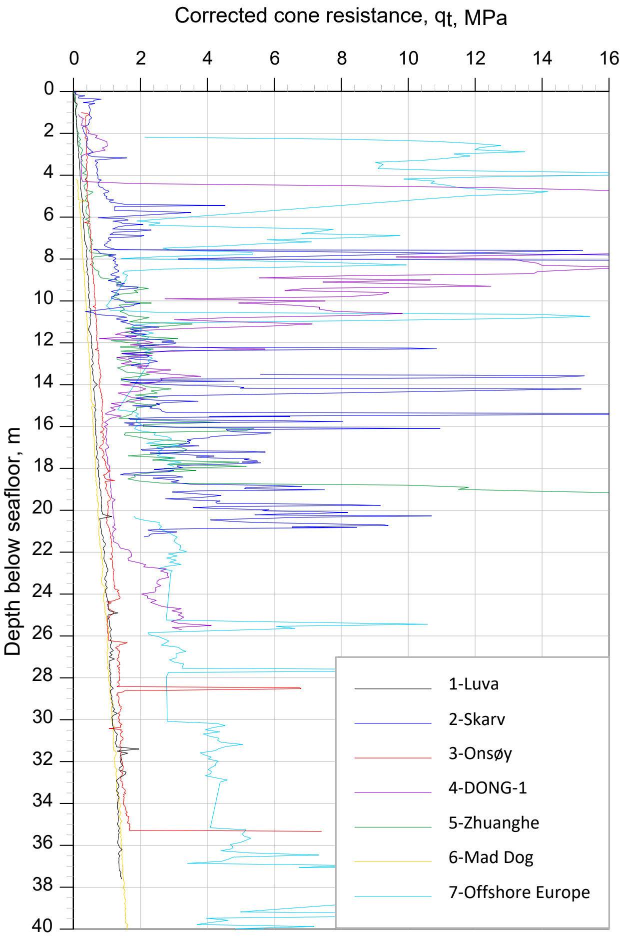


Figure 1 qt for soil profiles

deposit and/or the available data. A second diameter of 2 m was analysed to document the sensitivity to pile diameter. Although piles of 15 m length are rare in offshore projects, the method performance in shallower layers is still considered relevant for the purpose of this paper.

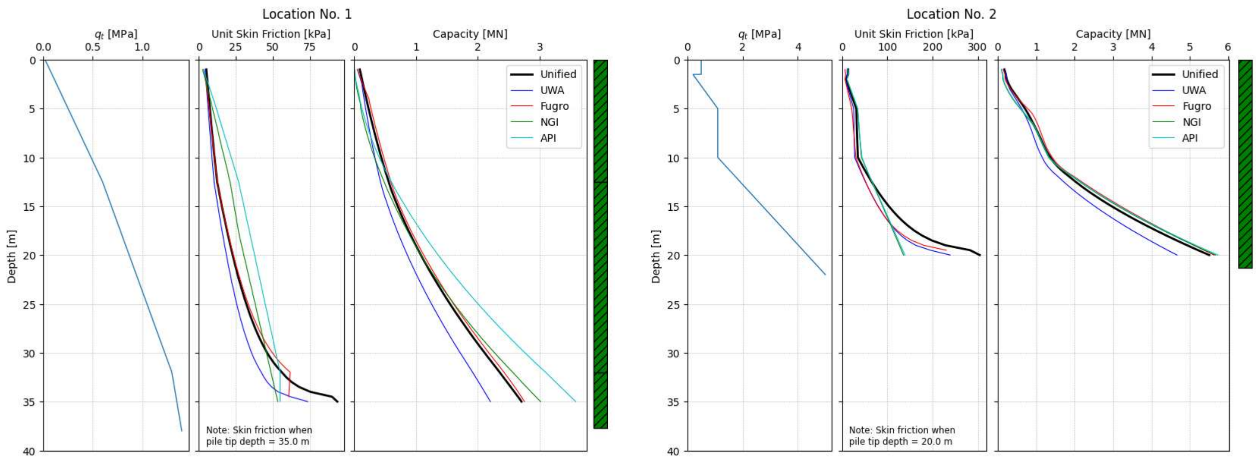
2.4 Parameter assumptions

Each of the capacity analysis methods require certain assumptions. In most cases, complete soil testing data was not available. Relevant soil parameters were therefore estimated as required for each method, based on experience and judgement. Where similar parameters are required for more than one method, the authors aimed for a consistent approach.

A primary assumption was to use an effective unit weight of soil of 4 kN/m^3 to 10 kN/m^3. For the API 2011 main text method and the NGI 2005 method, the undrained shear strength, s_u, was found by assuming N_{kt} in the range 12 to 18 and selecting a profile with depth. For NGI 2005, a plasticity index, I_p, of 30 % was selected.

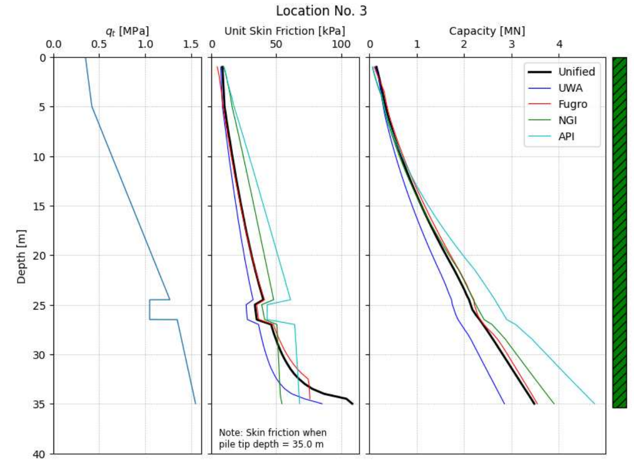
3 RESULTS

The soil profiles in Table 1 were analysed for the given pile geometries using each of the listed design methods. Results are presented as depth-wise profiles for each location in Figure 2. The first graph shows the idealised q_t profile, the second graph shows skin friction distribution with depth for the pile tip penetration given in the figure, and the third graph shows total axial bearing capacity from skin friction and end bearing for each method.. Figure 3 shows the results as relative distributions between the unified method and each of the other methods for pile diameters of 1 m and 2 m. All locations are combined in the relative distribution plots. Datapoints at a depth increment of 1 m between 15 m and 40 m were obtained.

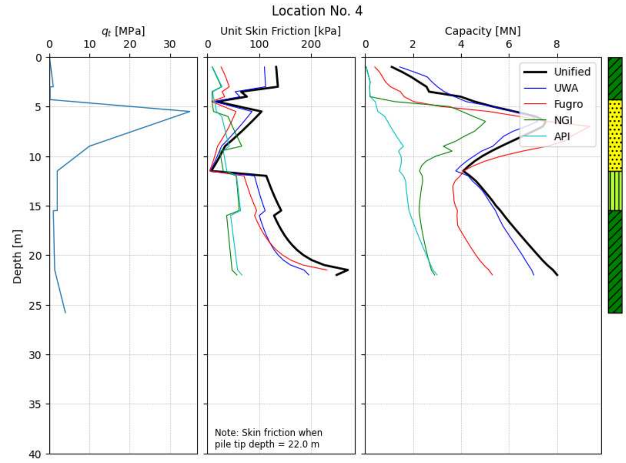


a) Figures for 1-Luva

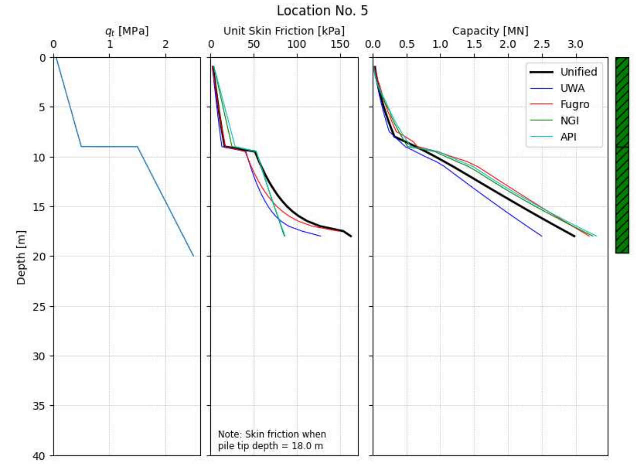
b) Figures for 2-Skarv



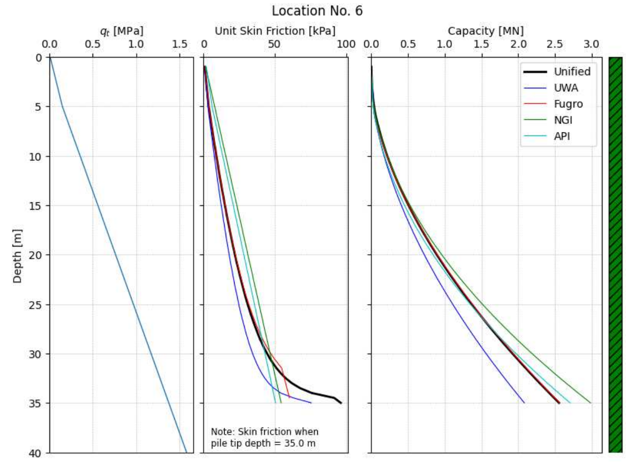
c) Figures for 3-Onsøy



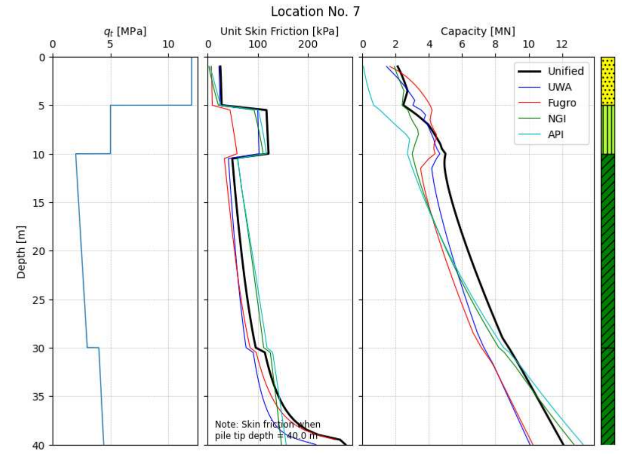
d) Figures for 4-DONG1



e) Figures for 5-Zhuanghe

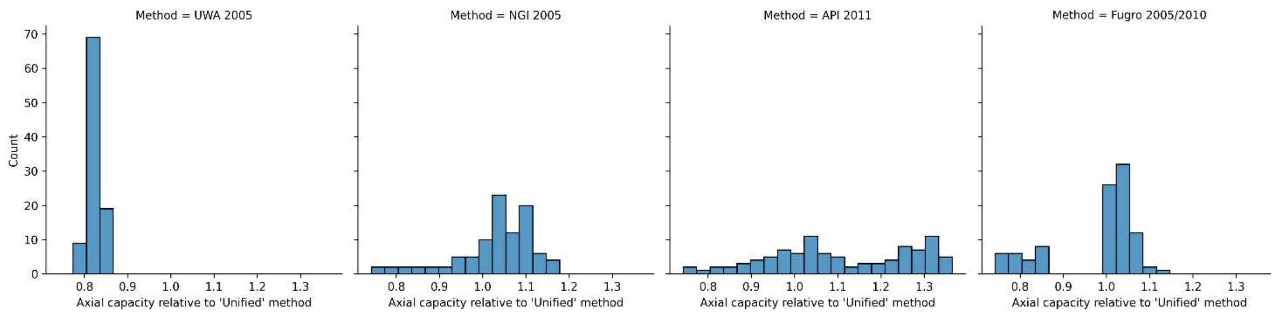


f) Figures for 6-Mad Dog

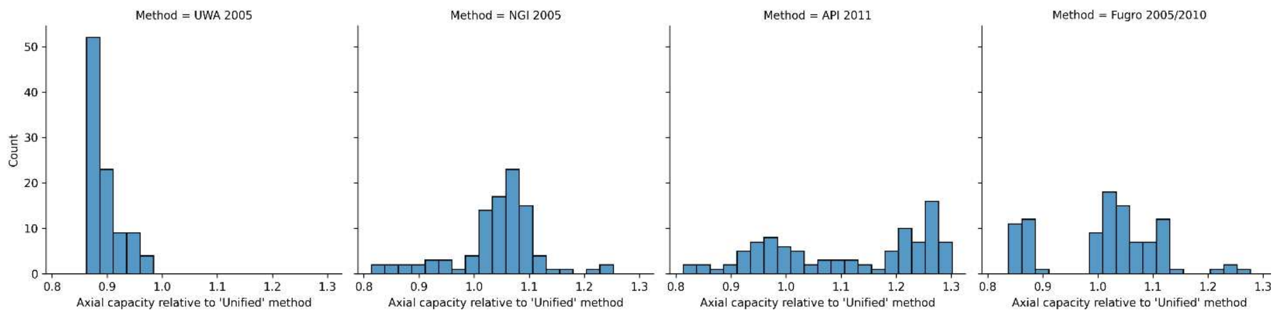


g) Fiures for 7 – Offshore Europe

Figure 2 Design profile q_t for each location and calculated total pile capacities with depth using 5 different methods



a) D = 1 m



b) D = 2 m

Figure 3 Relative distributions of total pile capacity

4 DISCUSSION

The results shown in this paper include a variety of soil profiles. The UWA 2005 method tends to predict pile capacities at the low end of the range given by the five methods for locations with pure clay profiles. The other methods predicting capacities at the higher end of the spectrum. Which method predicts the highest capacity is not consistent. The methods show differences in the distribution of skin friction that is consistent with the method formulations. The unified method shows the largest unit skin friction close to the pile tip of all the five methods. This highlights the importance of using a complete model where the skin friction along the whole pile including 'friction fatigue' and the pile tip resistance forms a coherent whole to calculate the pile capacity.

Comparing the capacities of each model relative to that of the Unified clear differences become evident. This is both in terms of the magnitude of the most expected value, and in the distributions of the relative capacities. The relative distributions show that the UWA 2005 method give capacities with a well-defined peak between 0.8 and 0.9 of the Unified method for both 1 and 2 m diameter. This is consistent with the similar mathematical formulations of the UWA and Unified methods. The peak shifts upward for increasing diameter indicating the Unified method has a smaller effect of diameter than the UWA 2005 method. This is understood as a consequence of how the h/D term with its exponent has changed between the UWA and Unified methods. The NGI 2005 method has a peak between 1.0 and 1.1 with a distribution spreading down to less than 0.8 for 1 m diameter and between 0.8 and 1.25 for 2 m diameter. It is possible this difference between diameters is an artefact of the number of soil results. The API 2011 method has a broad distribution without a single peak. Fugro 2005/10 show results that group appear to group around results between 0.8 and 0.9 and between 1.0 and 1.1.

The present study includes data from around the world. The authors encourage practitioners to investigate the use of the method and evaluate its applicability for their own project-specific cases, ideally publishing the results to share with the industry. For instance, additional data for sites with more highly over-consolidated clays would be of benefit to demonstrate the performance in a wider range of soil strengths than included in the present study. Studying the sensitivity of the results to the selection of soil parameters would add broader understanding. Further, one can also consider a greater range of pile geometries including closed-ended piles and piles with large diameters and larger pile lengths.

5 CONCLUSIONS

The Unified pile design method is based on the most comprehensive database of large-scale pile load tests available and was developed jointly by a team of experts across the industry representing the previously established methods. This paper presents case studies documenting the performance of this method for axial capacity of driven piles in clay for a variety of geological settings, depths and regions around the world compared to previously established methods. The results indicate that the Unified method give results that are comparable to the other methods accross a range of offshore conditions. These results, combined with the method‘s development, give confidence to a broader application for pile design in clay-dominated soil profiles offshore.

In conjunction with the unified sand method, this paper demonstrates that the geotechnical designer is equipped with two well-calibrated and reliable methods to provide sound and dependable capacities in a broad range of seabed soil profiles.

AUTHOR CONTRIBUTION STATEMENT

V Smith: Writing original draft, data collection, editing. **A. Senanayake**: Data analyses, **P. Jeanjean**: Manuscript review. **N. Morgan**: Manuscript review. **T. Langford**: Manuscript review.

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