EVALUATION OF NORWEGIAN DESIGN METHODS FOR AXIAL CAPACITY OF DRIVEN PILES IN SAND

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KEYWORDS

Driven piles, Piles in sand, Concrete piles, Steel piles, Axial capacity, Code of design

ABSTRACT

This study evaluates the Norwegian design methods for axial capacity of driven piles in sand referred to as the PV91 (β-method) and NGI-05 method. The two methods are based on different approach with different input parameters. The semi-empirical PV91-method is recommended to be used for preliminary design with a preference for NGI-05 method as primary design tool. However, since the NGI-05 method demands investigation of sand layers with CPT, the PV91-method serves as an alternative design approach when CPT data is unavailable. Thus, it is important that these two methods are evaluated on the same basis. In this work, a database consisting of 86 international pile tests in sandy soils are analysed and the prediction of shaft friction is evaluated for the PV91-method. PV91-method exhibits variability in axial capacity predictions but is shown to be highly conservative for densely and very densely deposited sand. For loose sand it is shown to overestimate shaft friction capacity for some pile tests. The NGI-05 method is evaluated in several database studies, showing greater accuracy than what the PV91-method performed in this database study. NGI-05 along with other CPT-methods tends also to overestimate capacity in some cases, and especially after friction capacity is corrected for ageing effects. This study offers guidance on the application of the methods and highlights areas for future improvement.

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1. INTRODUCTION

Various methods are employed for designing the axial capacity of friction piles in sandy soils. In Norway, the prevailing methods are the PV91-method (also known as the β-method) and the NGI-05 method [1, 5]. The PV91 is an empirical approach utilizing a fixed side friction factor β and is recommended for preliminary design in the Code of Practice for Piles 2019 [1] and NPRAs handbook V220 [5]. The PV91-method is in general regarded as a conservative approach for estimation of shaft resistance. On the other hand, the NGI-05 method is based on empirical correlations derived from Cone Penetration Test (CPT) data. Since the NGI-05 method demands investigation of sand layers with CPT, the PV91-method serves as an alternative design approach when CPT data is unavailable. CPT is not always available or possible to conduct in sandy soil deposits. This motivated the current study to systematically evaluate both methods based on the same basis. This helps designers to understand the implication of the adopted pile designs.

This article evaluates the semi-empirical method PV91with a database and compares it to the NGI-05 method and other available full scale pile load test databases. A discussion of the accuracy of the NGI-05 method compared to other frequently used CPT-methods based on former database studies is also presented. This study only focuses on the side friction capacity and does not evaluate the pile tip capacity.

2. DESIGN OF FRICTION PILES IN NORWAY

Norwegian design of the axial capacity of driven piles in sand is carried out using two methods referred to as the PV91 (β-method) and NGI-05 method [1, 5]. The empirical PV91-method calculates axial frictional capacity by estimating mobilized friction by use of a side friction factor β along the pile shaft, similar to the semi-empirical method API-RP2A method. The basis for β-values seem to be a redrawing of the comparison of β- values by Kraft & Focht [2] and is based on data from load tests for piles in clay, presented by Eide at a Pile Seminar in Norway in 1987 [3]. Soil density, pile length and mean effective vertical stress $\sigma'_{v;0}$ is necessary input for estimating shaft friction $\tau_{s;cal}$.

$$\tau_{s;cal} \qquad = \beta * \sigma'_{v;0}$$

Where β is the coefficient for the normalized side friction. The recommended value for beta is a function of pile length and sand density and is shown as the hatched area in Figure 1.

When CPT-data is available, the Code of Practice for Piles [1] recommends the CPT-based NGI-05 method [4], where side friction is directly correlated to relative density, which is calculated based on CPT-data. Characteristic side friction $\tau_{s;k}$ is calculated along the pile:

$$\tau_{s;k} = \frac{z}{z_t} * \sigma_a * F_{DR} * F_{last} * F_{spiss} * F_{mat} * F_{\sigma}$$

Where z/z_t is the relationship between depth and the final pile end depth, $\sigma_a$the atmospheric reference pressure, F_{last}, F_{spiss} and F_{mat} are coefficient for type of load, pile end geometry and material. F_{sigma} is a relationship between effective vertical stress and the reference pressure σ_a. F_{DR} is a factor based on the relative density, where the relative density is calculated based on empirical CPT-relations, which is specific for the NGI-method:

$$D_r = 0{,}4 * \ln\left[\frac{q_c}{22 * \left(\sigma'_{v;0} * \sigma_a\right)^{0{,}5}}\right]$$

3. THEORETICAL EVALUATION OF DESIGN METHODS

A theoretical comparison of normalized side friction for a selection of example piles is presented in Figure 1. Pile length of 20, 40 and 60 m is considered in sand with constant relative density of 0,4 (loose), 0,6 (medium dense) and 0,8 (dense). The comparison is made by back calculating the implied beta from the NGI-method by the formula $\beta = \frac{\tau_s}{\sigma_{v;0}'}$ based on the mentioned relative densities where $\sigma_{v;0}'$ is the mean effective stress for the pile lenght. Comparison between the range of beta factor for PV91-method and NGI-05 implied β-factor is shown in Figure 1.

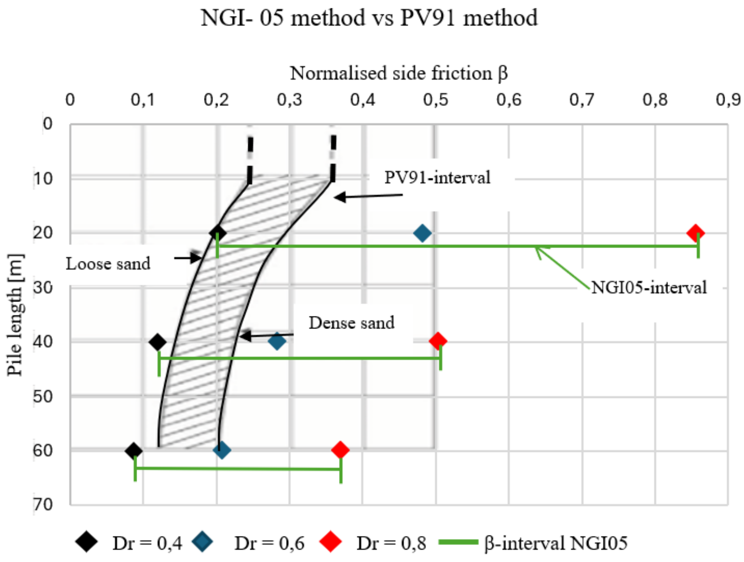

Figure 1 Comparison of normalized side friction factor β for PV91 and corresponding β as implied by NGI-05 back-calculated.

Normalized side friction interval from NGI-05 method is significantly larger than for PV91-method. For loose sand (Dr=0,4), both methods tend to give similar estimate of the side friction. For denser sand and shorter pile lengths the NGI-05 method predicts higher normalised side friction than the PV91. For the six theoretical example piles, the interval is approximately 3,5 – 6,5 times the size compared to the PV91-method. This is shown in table below.

Table 1. Comparison of β-values for example piles for PV91- and NGI05-method.

Pile lengths	**PV91**		**NGI05**		**NGI05 larger interval than PV91**
	β-values	**β-interval**	**β-values***	**β-interval***	
20	0,19 – 0,29	0,10	0,2 – 0,85	0,65	650%
40	0,14 – 0,22	0,08	0,12 – 0,5	0,38	475%
60	0,12 – 0,2	0,08	0,09 – 0,37	0,28	350%

*Back-calculated side friction factor β.

4. EVALUATON BASED ON DATABASES OF FULL-SCALE LOAD TESTS

4.2 Evaluation of PV91-method

Load tests results from three former database studies have been used in a database study for evaluation of the PV-91 method: NGI-99 database [7], ZJU-ICL database from 2015 [8] and pile load tests results from Leibniz University Hannover 2018 [9]. Acceptance criteria for the database required that load test results included information about pile type, loading method, measured failure load, CPT-data for estimating relative density (Dr) , soil layering and soil type. The database incorporates 23 tension tests from the NGI database, 23 tension tests and 20 compression tests from the ZJU-ICL database, and 6 tension tests from Leibniz University. The normalized side friction coefficient $\beta_{measured}$ was derived from the failure load and compared to βc_{PV91} from the PV91-method with the relation $\beta c_{PV91} / \beta_{measured}$. Ratio greater than 1 indicates PV91 overestimating the side friction.

The results presented in table indicates that the PV91-method greatly underpredicts shaft resistance, but the statistics indicators show that there are relatively large variations. Among all the samples, the 12 tests on concrete piles have the expectation value closest to 1, and they exhibit the lowest dispersion with a coefficient of variation of 0.44 but with the largest standard error. The expectation value for open-end steel piles is higher than for closed-end steel piles, but with a slightly higher coefficient of variation as well. Results indicate that PV91-method is more conservative for tension piles, than for compression piles.

Table 2. Statistical evaluation of PV91-method for selection of pile tests

	$\beta_{cPV91}/\beta_{measured}$				
Selection	Test piles	Mean μ	Standard deviation σ	Coefficient of variation CV	Standard error SE
All piles	86	0.57	0.30	0.53	3.2%
Tension load	66	0.54	0.27	0.50	3.3%
Compr. Load	20	0.66	0.35	0.53	7.8%
Open piles	52	0.59	0.31	0.53	4.3%
Closed piles	34	0.53	0.27	0.51	4.6%
Concrete piles	12	0.69	0.31	0.44	8.9%
Steel piles	74	0.55	0.29	0.53	3.3%
Time info.	58	0.54	0.30	0.56	3.9%
Closed end steel	23	0.45	0.20	0.42	4.1%
Open end steel	51	0.59	0.31	0.53	4.3%

Relative density Dr is the one known geotechnical parameter investigated by CPT for the database tests. Plotted graphically together with βc_{PV91} / $\beta_{measured}$. Ratio is shown in figure under.

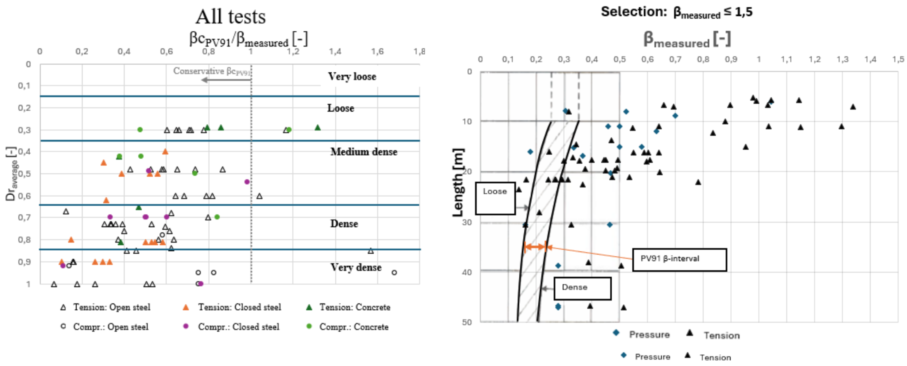

Figure 2 Left: The results are depicted with relative Density Dr. The blue lines represent the set limits for characterizing density of sand based on the classification from API [11]. Right: $\beta_{measured}$ vs pile length. Compared to PV91 interval of side friction factor β.

The three tests in loose sands with Dr = 0,3 where the method overestimates the capacity are tests from Norway (Larvik and Drammen). Of the 86 test piles there is only six test results where the PV91-method overestimates shaft capacity, and with mean value of 0,57 it mostly under predicts capacity with a significant margin.

Plotted beta values from the load tests vs the PV91-beta design interval is shown for the selection of tests with $\beta_{measured} < 1,5$ in **Feil! Fant ikke referansekilden.**.

Test results indicate a statistically skewness, suggestion that the PV91-method predicts shaft capacity more accurately in loosely deposited sand (Dr: 0.15 – 0.35) compared to moderately dense (Dr: 0.35 – 0.65) and dense/very dense deposited sand (Dr: 0.65 – 1.0), where the method offers significant conservative shaft capacity design for the pile tests in the database.

4.2 Evaluation of NGI-05 Method

Database studies by Schneider et al. [9], Yang et al. [8], and Lehane et al. [10] demonstrate stronger statistical outcomes (μ, CV) for CPT methods than for the API-RP2A method, and for findings of this study concerning the PV91-method. Because the CPT-methods are correlated to pile tests this is somewhat expected.

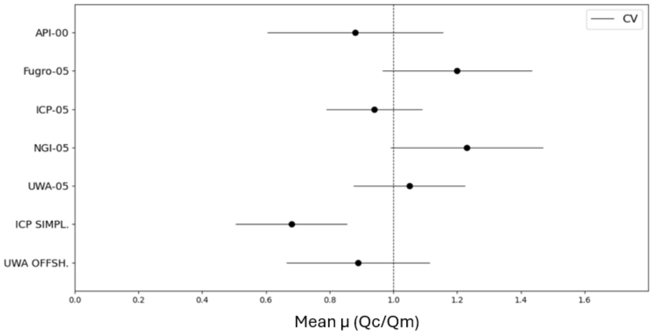

Figure 3 Expectation value μ and coefficient of variation CV: Total capacity of all 80 pile tests with time information in the database study by Yang et al. (2015). The results are not time corrected.

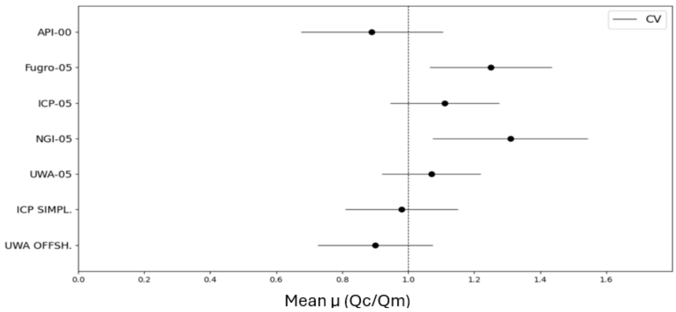

Figure 4 Expectation value μ and coefficient of variation CV: Total capacity for 41 time-corrected and weighted tests in the database study by Lehane et al. (2017).

The NGI-05 method, in several instances, demonstrates an overestimation of both side friction capacity and total capacity compared to pile tests in the database studies, particularly for calculated capacities scaled up using time correction factors. Although there are clear indications that the bearing capacity of friction piles in sand significantly increases with time (Karlsrud et al., 2014a), challenges are associated with increasing friction capacity for time effects in capacities calculated using CPT-based methods. Results from the study by Lehane et al. [10] and Yang et al. [8] shown in Figure 3 and Figure 4 indicate that this largely applies to the NGI-05, Fugro-05, and to some extent ICP-05 and UWA-05 methods, in which these methods can overestimate side friction when corrected for time effects.

5. FINAL REMARKS

This work evaluates the PV91-method's prediction of shaft capacity against an extensive database of pile tests. Some final remarks are listed below:

• The PV91-method is shown to be highly conservative for densely and very densely deposited sand. Pile tests have shown measured capacities for side friction much higher than those calculated using the PV91-method.

• The PV91-method's calculation of side friction is not necessarily conservative for piles in loosely deposited sand, or for piles in sand material with silt content. This is contrary to the current recommendation from Code of Practice for Piles [1]. For such cases, one should be cautious about scaling up the calculated bearing capacity with time effects in loose sands.

• Several database studies shows that CPT-based design methods for side friction demonstrate better predictions than the semi-empirical PV91-method and the API-RP2A method and should be used when there are available CPT-data.

Based on the results of this study, questions can be raised about whether the PV91-method should be updated and adjusted, given the current availability of numerous pile tests, and the large underestimation of friction capacity for denser sands. It is not always possible to attain CPT-results for pile sites, and there is a need for design methods without CPT data. Consideration about whether a higher relative density can be documented without CPT data in sandy materials should then be considered.

NGI-05 method was not calibrated for time corrections when the method was developed and the method tends to overestimate side friction capacity relative to pile tests in database studies [8,10], particularly when time correction factors are applied. Consequently, caution is advised when increasing the side friction bearing capacity calculated using the NGI-05 method with time effects, as allowed by Norway's Code of Practice for Piles [1].

Fugro-05, ICP-05, and UWA-05 may face similar challenges in accurately predicting capacities when adjusted for time effects.

Additionally, the evaluation of pile tip capacity using various calculation methods should also be addressed, which is not covered in this article.

REFERENCES

[1]Norwegian Geotechnical Society: Peleveiledningen 2019: Code of practice for piles, 2019. 380 pages. https://ngf.no/publikasjoner/peleveiledning-ikke-medlemmer/

[2] L.M. Kraft, J.A Focht, S. F, Anerasinghe: Closure to Friction Capacity of Piles Driven into Clay, 1981. Journal of Geotechnical Engineering, Volume 109, Issue 5

[3] O. Eide: Pelefundamentering: Åpning - dagens situasjon - Utfordring og muligheter, 1987. Unpublished paper presented at Kursdagene, NTH Trondheim

[4] C. Clausen, P. Aas, and K. Karlsrud: Bearing capacity of driven piles in sand, the NGI approach, 2005. Proceedings of International Symposium. on Frontiers in Offshore Geotechnics, Perth. s. 574-580

[5] Statens Vegvesen (Norwegian Public Road administration): N-V220 Geoteknikk i vegbygging, 2023 8.th version. https://viewers.vegnorm.vegvesen.no/product/859978

[6] F. Kolsgaard et al: Evaluering av beregningsmetoder for friksjonspeler i sand, 2020. Master thesis, Norwegian University of Science and Technology (NTNU). https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2779327

[7] C. Clausen, P, Aas.: Bearing Capacity of Driven Piles, Piles in Sand, 2001. Internal report NGI

[8] Z. Yang et al.: A Comprehensive Database of Tests on Axially Loaded Driven Piles in Sands, 2005. Academic Press, eBook ISBN: 9780128047484

[9] K. A. Schmoor et al.: Reliability of design approaches for axially loaded offshore piles and its consequences with respect to the North Sea, 2018. Journal of Rock Mechanics and Geotechnical Engineering, 10(6), s. 1112-1121

[10] B. Lehane et al.: Characteristics of unified databases for driven piles, 2017. Proceedings of 8th International Conference on Offshore Site Investigations and Geotechnics, SUT London. s. 162-194

[11] API: ANSI/API recommended practice 2GEO, 2014. API Washington, DC, USA