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Special Contribution

Updating Dutch national guidelines for determining the axial capacity of piles in sand

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Introduction

The Cone Penetration Test (CPT) developed in Delft in the 1950's provides a continuous indirect profile of the strength and stiffness of soil. The test is currently one of the most widely used in-situ test methods in both the onshore and offshore sectors. The widespread use of the CPT and the similarity between the stress-strain response during installation of the cone and displacement pile installation has resulted in the development of many direct correlations between CPT end resistance, q_c and pile resistance. In the current Dutch code, the pile shaft and base resistance components are linked directly to the cone end resistance, q_c measured during the CPT test using constant reduction factors α_s and α_p for the unit shaft, τ_f and the base resistance, $q_{b0.1}$ mobilised when the pile base displacement reaches 10% of the pile diameter:

$$\tau_f = \alpha_s \cdot q_c \quad (1)$$

$$q_{b0.1} = \alpha_p \cdot q_c \quad (2)$$

A range of constant α_s and α_p values for common pile types used in Dutch practice are shown in Table 1.

Table 1. α_p and α_s factors from the 2017 Dutch Standard.

Pile type	α_p	α_s
1. Driven pre-cast concrete closed-end	0.7	0.01
2. Driven Steel Tube with closed end	0.7	0.01
3. Driven Steel tube with open end	0.7	0.006
4. Screw injection Pile (SiP)	0.63	0.009

Because of the inherent variability of natural soils and the large strains necessary to form pile foundations, a number of features affecting the axial behaviour of deep foundations are poorly understood. Recent research on displacement pile behaviour indicates that the soil state around a pile that governs axial capacity is affected by issues such as cyclic degradation of shear stress due to installation (friction fatigue), residual stresses, soil ageing, plugging and pile roughness amongst other factors (Randolph 2003, Gavin et al. 2015 and Jardine 2019). For the displacement pile types no's 1 to 3 in Table 1 the α_s values from the current standards do not directly account for any of these impacts. The shaft and base resistance factors in Table 1 are amongst the highest values in use across Europe. However, Van Tol et al. (2015) note that there are hidden safety factors included in the design approach. One of which is that the design q_c value is limited. In Eqn.1 this limit is between 12 and 15 MPa, depending on the thickness of the soil layer. The design q_c used in Eqn.2 is determined using the Koppejan averaging technique. The base resistance determined is then limited to a upper-bound value of 15 MPa. This averaging method typically results in a lower design value than for other popular methods e.g. the French method where q_c design is determined by averaging q_c in the zone ±1.5D around the pile tip, See Gavin et al. (2019).

In order to update the Dutch design code a national research project was initiated with the aim to:

1. Perform full-scale pile tests in two distinct geological formations on the 3 most common pile types used in the Netherlands. These tests will be used to investigate installation effects, friction fatigue, residual stresses, ageing and whether limiting values of shaft and end bearing resistance are necessary for design.
2. Centrifuge tests will be performed in the small centrifuge at TU Delft and the large centrifuge at Deltares will investigate the effect of layering and CPT normalization method on the q_c reduction factors.
3. Through a combination of field measurements and probability based numerical modelling, pile design factors for use in design codes will be determined. Machine learning approaches will be investigated for developing geological and pile response models using more than 100,000 CPT profiles available at the first field test site located in the Port of Rotterdam.

4. Life-cycle analyses will consider the life-time capacity of the different pile systems (as influenced by both the geological and loading history) their costs (financial and environmental) and assess their long term impacts.

The project is being undertaken by a consortium including TU Delft, Deltares, Port of Rotterdam, Fugro, Rijkswaterstaat, Gemente Rotterdam and the Dutch Piling Association.

Work Completed to Date

The project started in October 2019. To date the first field test programme has been completed with a series of load tests being performed at in the Maasvlakte II region of the Port of Rotterdam in December 2019 and January 2020. Details of the test piles are given in Table 2.

Table 2. Piles tested at Port of Rotterdam

Pile type	Pile No.	Penetration Length (m)
Driven pre-cast concrete	1	31.74
0.4m square	2	31.29
	3	31.80
Driven Steel Tube with closed end	4	32.50
Shaft casing diameter 0.38m	5	32.47
Base plate width 0.48m	6	32.47
	7	32.46
Screw injection Pile (SiP)	8	37.02
Shaft casing diameter 0.61m	9	37.06
Pile base diameter 0.85m	10	34.98
	11	34.02

The CPT profiles at the test site are shown in Fig. 1a. The soil profile consists of a recent upper fill layer of sand (less than 10m thick) underlain by a mostly sand deposit interbedded with clay layers. Very strong Pleistocene sand deposits were located at approximately 29m below ground level with CPT values ranging from 20 to 80 MPa. This deposit was also interbedded with occasional thin, stiff clay layers. The test pile lengths were chosen such that all test piles were installed with the pile tip between 7 and 11 pile diameters in the very strong Pleistocene sand layer. The piles were all instrumented with two fiber optic strain gauge systems, BOFDA's that provide a continuous profile of strain along the pile depth and Fiber Bragg Gratings, FBGs that provide discrete measurements. The test site is shown in Figure 1b.

(a) (b)

Fig. 1. (a) CPT profile at the test site (b) Set-up of the load test frame over one pile

The load-displacement response of the driven square precast concrete piles are shown in Fig. 2. The first two tests were performed between 4 and 5 weeks after installation. In order to check whether an additional aging period provided enhanced the final pile was tested 11 weeks after installation. The overall load-displacement response of all piles was similar. The driven steel tubes developed capacities of between ≈ 7MN and 9.5 MN. In order to check the sensitivity of the resistance of SiP piles to the q_c in the vicinity of the pile base, two piles were installed to shorter lengths with the bases near the weaker sand layer. The shorter piles had capacities of 18-19 MN, whilst the longer piles developed capacities of 21 to 24 MN. The results of the tests are currently being analysed and reports are being prepared with updated α_s and α_p values and recommendations for the adoption of unlimited q_c values in Eqn's 1 and 2. According to the national design rules these results can only be applied at this site or one with very similar soil conditions. In order to change the values in Table 1 a 2nd test site in a geologically diverse material is required.

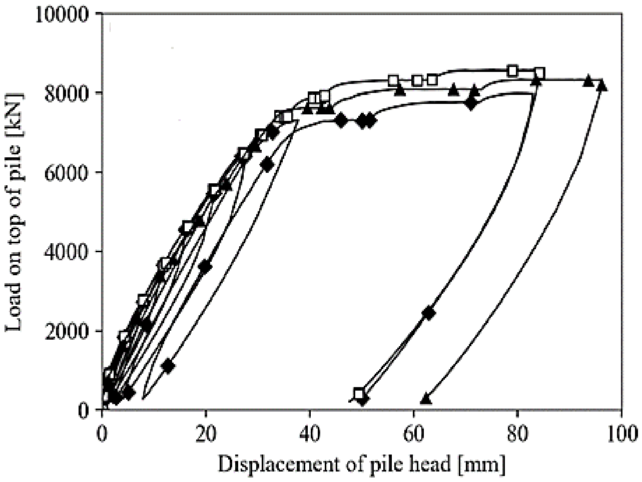

Fig. 2. Load-displacement test results from driven concrete piles at Port of Rotterdam

Work Ongoing

The Maasvlakte is an area of reclaimed land and therefore the ground conditions e.g. the absence of upper soft organic deltaic soils evident over much of the Western Netherlands and the very high CPT values of the deep Pleistocene sand are not typical Dutch soil conditions. They even differ from the conditions found in the city of Rotterdam and the majority of the Port area. In order to verify if the findings from this test site are nationally applicable a second test in more typical conditions is required. The Randstad is a megalopolis containing the four biggest cities (Amsterdam, Rotterdam, The Hague and Utrecht) in the Netherlands, the ports of Rotterdam and Amsterdam along with Schiphol airport. The region is home to half the population of the Netherlands. The majority of this area is underlain by the Kreftenheye formation derived from fluvial deposits originating from the Rhine river system. A sand layer with CPT q_c values typically between 15 MPa and 60 MPa is found at about 20m to 25m below ground level in this formation. The 2nd test site for the project was chosen at the headquarters of project partner Deltares. The CPT profile at the site is shown in Fig. 3a, the piles will be installed to the lower sand layer with CPT q_c of around 15 to 30 MPa.

Centrifuge testing will involve creating uniform sand samples at a range of q_c value from 10 to 50 MPa in order to investigate limiting shaft and base resistance values. In addition the effect of layering on pile base resistance will be undertaken. The tests will be performed in the small centrifuge at TU Delft and a new centrifuge that will be opened in Deltares in 2020. This new facility is an Actidyn C72-31 beam type centrifuge, with a platform radius of 5.0 m, See Fig. 3b. The project expects to provide an updated National guideline document by 2022.

(a)

(b)

Fig. 3. (a) CPT Profile at the 2nd test site (b) Geo-Centrifuge at Deltares

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A brief CV of Prof. Kenneth Gavin

Kenneth Gavin is a Professor of Subsurface Engineering at TU Delft since April 2016. He received his Bachelor’s degree from Queens University Belfast in 1994 and his PhD in Geotechnical Engineering from Trinity College Dublin in 1998. Ken worked for Arup Consulting Engineers before moving to University College Dublin in 2001. His main fields of research relate to the performance of pile foundations and the impact of climate change of civil engineering infrastructure. In the area of pile foundations, he has been involved in a number of Joint Industry Projects in the offshore wind sector. Regarding the impact of climate change he has led a number of European collaborative research projects with a particular focus on ageing rail infrastructure. Throughout his academic career Ken has continued to provide consulting services on technically challenging projects across the globe.